11TH INTERNATIONAL CONFERENCE ON INDUSTRIAL ECOLOGY

JULY 2-5 2023

International Society for Industrial Ecology

Conference Proceedings

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Welcome to the 11th International Conference on Industrial Ecology (ISIE2023) of the International Society for Industrial Ecology. Following a lengthy delay caused by Covid19, we're excited that the conference makes its way back to Leiden, the Netherlands, where the first ISIE conference was held in 2001.

The theme of the conference is Transitions in a world in turmoil. The way we use energy and resources in our present system is not sustainable. Major changes are necessary in our energy system to make it climate-neutral. At the same time our use of land, water and material resources needs to change dramatically to become sustainable. To avoid further deterioration of nature and our environment and resource supply constraints we must move toward a circular economy, while at the same time ensuring equitable transitions. The Covid19 crisis and the Russian aggression in Ukraine have caused have changed the geopolitical context in which these transitions will have to take place. During the conference, we will discuss the challenges the world is facing, the changes that are necessary to remain within planetary boundaries, and the solutions that could be employed in a technical, behavioural and organisational sense to meet these challenges.

Contact information:
email: isie2023@crawfield.nl
Website: https://isie2023netherlands.nl/
For urgent matters during the conference you can also get support from the reception desk at the KOG building or call +31-85-401-3986. This number is available 8:00-18:00 from Saturday 1 July to Wednesday 5 July.

Conference venues addresses:
Stadsgehoorzaal - Keynotes and opening/closing sessions venue Breestraat 60, 2311 CS Leiden
Pieterskerk - Poster sessions venue Kloksteeg 16, 2311 SL Leiden
Kamerlingh Onnes Building (KOG) - Parallel sessions venue Steenschuur 25, 2311 ES Leiden
Naturalis - Conference dinner venue Darwinweg 2, 2333 CR Leiden

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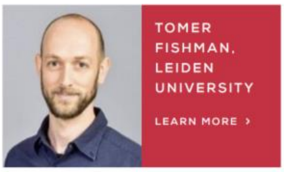

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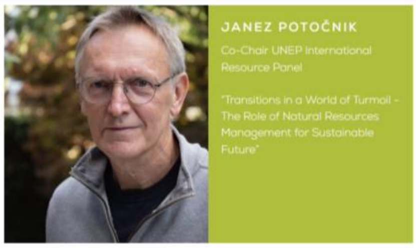
Keynote speakers



	Saturday 1 July	Sunday 2 July	Monday 3 July	Tuesday 4 July	Wednesday 5 July
9:00	ISIE 2023 Leiden	Registration (SGZ, from 8:00)	Parallel sessions (KOG)	Parallel sessions (KOG)	Parallel sessions (KOG)
9:30					
10:00	Pre-conference events: (separate registration required)	Opening session (SGZ)			
10:30	SIEYP (Symposium on Industrial Ecology for Young Professionals)	Plenary keynote (SGZ)	coffee break (KOG)	coffee break (KOG)	coffee break (KOG)
11:00			Parallel keynotes (KOG)	Parallel keynotes (KOG)	Parallel sessions (KOG)
11:30	IRTC raw material risks workshop	coffee break (SGZ)	Break	Break	
12:00	Symbiosis section symposium	Plenary keynote (SGZ)	Short parallel sessions (KOG)	Short parallel sessions (KOG)	
12:30				Lunch (KOG)	Lunch (SGZ)
13:00		Poster sessions with Lunch (Pieterskerk)	Poster sessions with Lunch (Pieterskerk)		
13:30					
14:00				Excursions, individual time	Plenary keynote (SGZ)
14:30					Closing session (SGZ)
15:00	Welcome reception (1st time slot) (Leiden city hall)	Parallel sessions (KOG)	Parallel sessions (KOG)		
15:30					
16:00		coffee break (KOG)	coffee break (KOG)		
16:30	Welcome reception (2nd time slot) (Leiden city hall)	Parallel sessions (KOG)	Parallel sessions (KOG)		
17:00					
17:30					
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International Society for Industrial Ecology

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Advancements in MFA methods 1

A Framework of Digital Twin-driven Material Flow Analysis (DT-MFA): Demonstrated by Mapping Regional Nutrients Flow

Sunday, 2nd July - 15:00: Advancements in MFA methods 1 (C1.31 KOG)

Wei Zhang [1], ***Thomas To-Hung TSUI*** [2], ***Purusothmn Nair*** [1], ***Bhawana Gupta*** [3], ***Nadja Yang*** [1], ***Saher Hasnain*** [3], ***Kok Siew Ng*** [1], ***Aidong Yang*** [1]

1. *University of Oxford,* ***2.*** *Department of Engineering Science, University of Oxford,* ***3.*** *Environmental Change Institute, University of Oxford*

Material flow analysis[1] (MFA) is one of the central methodologies of industrial ecology to map and quantify the efficiency of material uses for a variety of purposes[2,3] such as providing support for policy-making to achieve sustainable development goals. The precision and reliability of MFA results play a crucial role in making appropriate decisions. However, the quality of obtained results is often difficult to be directly assessed due to the complex nature of the MFA models and data. Hence, it is highly desirable to develop an effective technique to quantify the impact of the models and data on MFA results.

Digital twin[4](DT), which is a virtual representation of a real-world system (or entity), is considered an emerging and vital technology for better decision-making. Since originally proposed two decades ago, the concept of digital twin has been successfully applied to a large number of complex systems in various fields to perform tasks such as model update, system identification, uncertainty quantification, reliability analysis, structural health monitoring, and optimization design. The successful implementation of these tasks can provide significant benefits for the assessment and improvement of MFA results.

Although many studies focused on the investigations of MFA with complex systems and/or uncertain data, digital twin modelling and the related techniques were seldom systematically reported to assess and improve the precision and reliability of MFA results[5]. To better understand the potential of digital twin-driven MFA (DT-MFA) and to facilitate its applications, two fundamental questions need to be addressed: (1) What is a DT-MFA, and what are its benefits and opportunities for improving MFA? (2) how does DT-MFA work, and are there general principles that could direct its development?

To address the above questions, this work aims to:

- Provide a summary and analysis of the current digital twin models in connection with MFA applications to identify the advantages and gaps of DT-MFA.
- Investigate the basic principles and a general framework of DT-MFA and the enabling technologies and tools accessible in it to guide its theoretical development and practical applications.

In this work, an overview of DT-MFA and its practical framework with general principles is first proposed. A case study of Leicestershire County and Leicester City, UK organic waste management is developed to demonstrate the effectiveness of the proposed DT-MFA method for exploring the options of nutrient recovery. Finally, observations and future research recommendations such as data collection guidelines, model update strategies, and uncertainty treatment methodologies of DT-MFA are presented. This work provides fresh insights for DT-MFA which can inform MFA practitioners of the potential of digital twin techniques as effective tools for industrial ecology in the era of digital transformation.

References:

1. Brunner, P. H. & Rechberger, H. *Handbook of material flow analysis: for environmental, resource, and waste engineers, 2nd Edition.* (CRC Press, 2017).

2. Streeck, J., Pauliuk, S., Wieland, H. & Wiedenhofer, D. A review of methods to trace material flows into final products in dynamic material flow analysis. *J. Ind. Ecol.* jiec.13380 (2023) .

3. Haberl, H. *et al.* Contributions of sociometabolic research to sustainability science. *Nat. Sustain.* **2**, 173–184 (2019).

4. Tao, F. & Qi, Q. Make more digital twins. *Nature* **573**, 490–491 (2019).

5. Huang, Y. *et al.* Forward-Looking Roadmaps for Long-Term Continuous Water Quality Monitoring: Bottlenecks, Innovations, and Prospects in a Critical Review. *Environ. Sci. Technol.* **56**, 5334–5354 (2022).

Digital twin by machine learning in MFA reconstruction of biomass valorization

Sunday, 2nd July - 15:15: Advancements in MFA methods 1 (C1.31 KOG)

Thomas To-Hung TSUI [1]***, Wei Zhang*** [1]***, Kok Siew Ng*** [1]***, Aidong Yang*** [1]

1. *University of Oxford*

Valorization of biomass resources is key to improving resource efficiency in a circular bioeconomy. The research direction would encourage more innovative and efficient utilization of biomass residues (e.g. food waste, sewage sludge, and agricultural biomass). With the emergence of more technoscientific advancements in place, a comprehensive understanding of how they could impact the regional mass flow is necessary to support decision-making during infrastructure planning[1]. In contrast to other recycling activities, the valorization of biomass resources often entails integrated engineering systems of high-dimensional complexity involving biotechnological and thermochemical processes. The scaling factors and many other non-linear relationships are posing methodological challenges as a part of the systems approach in exploring new resource loops in our supply chain.

On the other hand, the development of digital twins for urban systems has been growing alongside artificial intelligence innovations in computing and visualization[2], including building information models and three-dimensional city models. They take place against a backdrop of digital transformation, which is happening in many industries and academic disciplines to address the growing sustainability challenges in urban systems. While these digital twins provide a general digitalization of the built environment, it would be beneficial if the bidirectional characteristics of human activities (at more precise spatial and temporal scales) could also be connected to improve waste management practices. The seamless applications of digital twins for biomass valorization are challenging, where it will need the massive development of dynamic models that can capture rapid technological progress and also be effectively incorporated into reconstructing material flow analysis (MFA). Compared to the conventional approach of mechanistic modeling for technological systems, the recent advancements in machine learning algorithms provide more accessible opportunities for developing predictive models that can directly build on available data. There will be benefits but also constraints of machine learning on biomass valorization.

As a subsystem of MFA in recent Agile Initiatives (hosted by Oxford Martin School)[3], the current results have presented wastewater treatment plants of great influence in regional resource efficiency. Using sewage sludge as a case, this presentation will share the lesson learned of necessary MFA reconstruction by machine learning in the future transition towards digital twins. Built on the experiential process by practice, we identified challenges and opportunities of the digital twin development on sewage sludge (also transferable to biomass valorization of other waste streams). They are classified into three aspects below:

1) benefits and constraints of machine learning on biomass valorization,

2) develop principles to reduce system complexity for implementation, and

3) help achieve global equity to technoscientific progress.

To that end, resource circularity in urban systems could be guided by high-resolution accounts of tradeoffs from different technoscientific advancements. The more progressive dialogue will encourage the requirements of biomass valorization for infrastructure choices in future urban systems.

COMPARISON OF MATERIAL AND ELEMENTAL FLOWS IN INDUSTRIAL NETWORKS OF TWO US REGIONS USING PIOT HUB – A NOVEL CLOUD BASED COMPUTATIONAL TOOL

Sunday, 2nd July - 15:30: Advancements in MFA methods 1 (C1.31 KOG)

Apoorva Bademi [1], *William Farlessyost* [1], *Shweta Singh* [1]

1. Purdue University

An important goal of industrial ecology is to ensure a balance is maintained between economic and environmental sustainability. Facilitation of this balance requires an understanding of the structure of the material economy and the material flows/waste generation in industrial networks in order to minimize the environmental consequences of these industrial systems. Physical Input-Output Tables (PIOTs) are uniquely suited for this purpose by mapping physical flows between industrial sectors. In previous work, PIOT-Hub was developed to automate the generation of both Physical Supply Tables (PSTs) and Physical Use Tables (PUTs) as well as their conversion into PIOTs by integrating the strength of mechanistic models and macroeconomic Input-Output framework [1]. Hence, PIOT-Hub, a cloud-based tool, can be used to generate the PST and PUT for a region using a bottom-up approach where relevant industrial processes are simulated via mechanistic models to determine steady-state material input and output requirements. Thus, the tool establishes a connection between engineering and economic models providing insight for transitioning to a low carbon and zero waste circular economy. In past work, PIOT-Hub was applied to 11 agro-based economic sectors in Illinois, thus capturing elemental flows across the economy, demonstrating the automation aspect. Here we evaluate the reproducibility and time-consumptive aspects of PIOT-Hub by mapping the material flows of equivalent economic sectors in Indiana. This work not only demonstrates the tool's reproducibility and transferability to other geographic regions, but also serves as a case study illustrating how the PSTs, PUTs, and PIOTs recovered by PIOT-Hub can be used to compare the material economies between regions. We perform a comparative analysis of material and elemental flows in two regions, Illinois and Indiana, using our work and the PIOT generated for Illinois in previous work. We further compare these material flows with those derived from the monetary IO data, obtained from the Industrial Ecology Laboratory, for each of the regions [2]. Certain circular economy scenarios are modelled to study how these affect the recycling of Carbon and Nitrogen in the industrial network. We will also demonstrate the collaborative aspect of this computational tool by live demo of the tool during this talk, thus highlighting the scaling impact of collaboration through cloud-based platform in making sustainable manufacturing decisions.

Expert Elicitation and Data Noise Learning for Material Flow Analysis using Bayesian Inference

Sunday, 2nd July - 15:45: Advancements in MFA methods 1 (C1.31 KOG)

Daniel Cooper [1], ***Shelie Miller*** [1], ***Jiankan Liao*** [1], ***Xun Huan*** [1]

1. *University of Michigan*

Material flow analysis (MFA) is a foundational tool of industrial ecology research and characterizes how a given material is transported and transformed through a supply chain. MFAs are key to identifying potential resource efficiency improvements (e.g., increased recycling), and to evaluating the upstream and downstream system impacts of local interventions; e.g., the potential to reduce greenhouse gas (GHG) emissions released during material production by improving downstream manufacturing process yields. MFAs have been used to help set environmental policies and goals by national governments (e.g., justifying Japan's reduce, reuse, and recycling laws), local governments (e.g., remedial action taken against toxic releases into New York City harbor), and companies (e.g., Toyota's corporate MFA was used to set company goals for emissions and recycling). The proliferation of MFA, however, is hindered by at least two major challenges. First is the long timeline for creating and updating detailed MFAs, currently taking months or even years. Second is the lack of uncertainty quantification (UQ) in most MFA results—a lack of UQ limits insight into the impacts, risks and unintended consequences of system interventions. It is increasingly accepted that UQ must be included in MFA results if they are to meaningful and support informed decision- and policy-making. Bayesian methods help address these challenges of UQ and laboriousness in MFA.

Bayesian inference allows the transparent communication of uncertainty in material flow analyses (MFAs), and a systematic update of uncertainty as new data become available. However, the method is undermined by the difficultly of defining proper priors for the MFA parameters and quantifying the noise in the collected data. We start to address these issues by first deriving and implementing an expert elicitation procedure suitable for generating MFA parameter priors. Second, we propose to learn the data noise concurrent with the parametric uncertainty. These methods are demonstrated using a case study on the 2012 U.S. steel flow. Eight experts are interviewed to elicit distributions on steel flow uncertainty from raw materials to intermediate goods. The experts' distributions are combined and weighted according to the expertise demonstrated in response to seeding questions. These aggregated distributions form our model parameters' prior. A sensible, weakly-informative prior is also adopted for learning the data noise. Bayesian inference is then performed to update the parametric and data noise uncertainty given MFA data collected from the United States Geological Survey (USGS) and the World Steel Association (WSA). The results show a reduction in MFA parametric uncertainty when incorporating the collected data. Only a modest reduction in data noise uncertainty was observed; however, greater reductions were achieved when using data from multiple years in the inference. These methods generate transparent MFA and data noise uncertainties learned from data rather than pre-assumed data noise levels, providing a more robust basis for decision-making that affects the system.

LCA case studies 1

Crab cravings in China causes environmental pressure

Sunday, 2nd July - 15:00: LCA case studies 1 (A1.44 KOG)

Xin LIU [1]

***1.** Nanjing University*

The increasing human demand for high-quality animal protein has provided impetus for the development of aquaculture, especially for countries like China. Such rapid development of aquaculture in part rely on added feeds, drugs and chemicals to improve productivity, and can have negative environmental impacts. To comprehensively quantify those impacts, life cycle assessment (LCA) studies have been conducted on different aquaculture commodities. However, scientific literature documenting environmental pressures related to crab culture is very scarce. Chinese mitten crab (*Eriocheir sinensis*), a brownish crustacean that is normally regarded as one of the world's most notorious aquatic invasive species, is rapidly being cultured in freshwater ponds in China, with the annual production tripling from 232 kt in 2000 to over 750 kt in 2018, representing nearly all of global production. Therefore, this study aims to explore the spatiotemporal evolution of crab culture in China since the 2000s and evaluate the environmental impacts along its life-cycle stages: megalopa, juvenile crab, and adult crab cultivation. The geostatistical analysis showed a more dispersed pattern of crab culture nationally as crab grows, with coastal provinces that have brackish water for megalopa cultivation but larger spatial coverage for juvenile and adult crab cultivation. However, contrary to the spatial expansion of juvenile and adult crab cultivation over time, megalopa cultivation became more spatially concentrated, of which the centroid moved south and formed one major cluster in Jiangsu Province, accounting for 89% of megalopa production in 2018. The centroid of juvenile crab cultivation remained in the east over these years while that of adult crab cultivation shifted toward more inland areas. Overall, 1 ton live-weight of crab produced in China generated 7.65 ton of CO_2 eq of greenhouse gas emissions, about 50% higher than the estimates for finfish fish production from previous studies (5.1 ton of CO_2 eq). Most environmental pressures occurred at the stage of adult crab cultivation, of which the upstream processes of electricity and feed production are important contributors. We further compared the environmental impacts between different production systems and found that crab culture in lakes resulted in lower global warming, acidification, ecotoxicity impacts, and energy use, but higher eutrophication impacts than more intensive pond systems. This work adds to the literature by understanding the temporal and spatial changes of crab culture boom in China and constructing a representative life cycle data pool to broaden the benchmark knowledge of its environmental pressures. We highlight the trade-offs between localized and global environmental consequences to promote sustainable aquaculture growth.

Recent trends in the carbon footprint of Peruvian dietary patterns based on the national household survey

Sunday, 2nd July - 15:15: LCA case studies 1 (A1.44 KOG)

Ian Vazquez-Rowe [1], *Joan Sanchez-Matos* [1], *Ramzy Kahhat* [1]

1. *Pontificia Universidad Católica del Perú*

In most regions of Peru, food purchase accounts for approximately 50% of household expenditure. This may imply that food expenditure accounts for an important fraction of per capita environmental burdens, especially in areas where the diet is based on higher consumption of red meat. Therefore, the main objective of the current study was to revisit the GHG emissions linked to Peruvian dietary patterns using recent household survey data for the period 2019-2022. The utility of this study is two-fold. On the one hand, it allows performing a direct comparison with the GHG emissions results that have already been obtained for Peruvian diets in the period 2008-2009, identifying changes in food consumption and analyzing current trends, including the effects of the COVID-19 on food purchase and consumption. On the other hand, these updated results allow a more accurate analysis of how the food sector is contributing to national GHG emissions in Peru and understand to what extent national dietary patterns are within the required planetary boundaries and the 2030 Paris commitments. The national household survey (i.e., ENAHO, following the acronym in Spanish) was used to extract data linked to food consumption for a wide range of food products. These were, thereafter, processed from a temporal (i.e., on annual and monthly basis) and geographical (i.e., average Peruvian values, per region and for major cities) perspective. GHG emission factors were obtained for all food and beverage items included in the study, based on data availability at a Peruvian, regional or global level, depending on data availability and quality. The results, which are still being processed, demonstrate that there was an important decrease in consumption in certain food and beverage items during the months of draconian lockdown between March and June 2020, especially for the most expensive food products in the basket (e.g., pork and beef), but that soon the consumption patterns levelled out to pre-pandemic levels. Hence, 2020 showed substantially lower GHG emissions per capita as compared to years 2019, 2021, and 2022. When compared to the diet observed for Peru in 2008-2009, GHG emissions were found to have increased slightly in a decade due to a higher consumption per capita of high-carbon products (e.g., beef) and an increase in food purchase in lower socioeconomic levels. We expect that the full results, once processed, will allow establishing how Peruvian diets perform from a nutritional and environmental perspective and will help in establishing public policies for GHG emissions mitigation.

Evaluating the environmental impacts of U.S. historical oil spill incidents from the life cycle perspective

Sunday, 2nd July - 15:30: LCA case studies 1 (A1.44 KOG)

Yiming Liu [1], *Hua Cai* [1]

1. Purdue University

Producing and using a product exposes us to risks of releasing it to the environment, which may cause damages to the ecological environment and impact human health. One such example is oil products. Although there were only two extremely large oil spill disasters in the past thirty years (Gulf War Oil Spill in 1991 and Deepwater Horizon Oil Spill in 2010), multiple smaller oil spills happened every year and resulted significant amount of oil release. The spill incidents happened in different life cycle stages and processes of oil production (such as drilling, transportation, refining, and use) are also impacting different environmental compartments (e.g., ocean, river, road) and releasing different products (e.g., crude oil versus more refined products). Understanding the environmental impacts of historical oil spill incidents associated with different life cycle stages and processes of oil production can help us better assess the environmental risks of producing and consuming oil, which is not captured by existing life cycle framework.

To address the above mentioned need, this work first developed an oil spill incidents database with refined spilled amount, covering the period from 1957 to 2022. We used the Raw Incident data provided by National Oceanic and Atmospheric Administration (NOAA) and United States Coast Guard (USCG) as input and identified the amount of released oil using a combination of different data sources. Based on where and how an incident happened, each incident is then matched with a life cycle stage/process. Based on a thorough literature review of environmental, ecological, and economic impacts of oil spill, we also developed a framework to estimate the impact of each incident. Last, we conduct statistical analysis to evaluate the environmental impact and risks of oil spill in each life cycle stage/process.

Modelling the complex environmental impacts of global freight transport in LCA

Sunday, 2nd July - 15:45: LCA case studies 1 (A1.44 KOG)

Christopher Oberschelp [1], ***Jan Lordieck*** [2], ***Tobias Rieder*** [2], ***Andreas Froemelt*** [3], ***Akshat Sudheshwar*** [4], ***Ueli Haefeli*** [5]

1. *ETH Zurich,* ***2.*** *Rapp AG,* ***3.*** *Eawag,* ***4.*** *EMPA,* ***5.*** *Interface Politikstudien Forschung Beratung AG*

The transport sector - including freight transport - is the main consumer of liquid fossil fuels globally and thus results not only in massive amounts of greenhouse gas emissions, but is furthermore a main source of human health impacts due to emissions of particulate matter (PM), sulphur dioxide (SO2) and nitrogen oxides (NOx). For effective reduction of environmental health burdens, freight transport can be evaluated by life cycle assessment (LCA), but so far, the implementation of freight transport in LCA studies and background databases remains strongly oversimplified by neglecting complex logistics chains across different companies, the locations of logistics hubs, the diversity in transport means and the variability in loading. The present research will aim to address this problem by (a) developing a model to mimic the complex supply chains in the global freight transportation sector, (b) applying the model to a number of case studies in order to quantify the related environmental impacts, and (c) analyzing the systematic deviations in environmental and health impacts in comparison to conventional freight transportation models in LCA.

A global model for freight transportation is developed that works with a number of key parameters as inputs (freight type, mode preference, start and destination, express transportation, cooled or frozen transport, storage) and combines these with an extensive database of global freight infrastructure (transportation hubs, possible routes, etc.). Depending on the input parameters, realistic logistics chains along several types of transport infrastructure (such as rail yards, harbors, warehouses, sorting centers, distribution bases, etc.) are generated and subsequently in a Monte Carlo simulation linked to the real-world infrastructure. Then, transport means are selected and optimal routes (based on costs, distances, time or environmental impacts) are calculated. Emissions and environmental impacts along the transportation routes are calculated based on the transport means, assuming a distribution of load and hence also emission intensity per amount of freight transport. The outcomes are then weighted and compared against freight transportation data in the ecoinvent LCI (life cycle inventory) database.

The comparison of environmental impact distribution between detailed assessment of logistics chains and simplified approaches as used in the ecoinvent LCI database shows a strong mismatch for several types of freight transport that frequently exceeds resulting LCIA scores by more than 45%. In part, this is because the ecoinvent database uses generic freight statistics data from the US for all regions of the world for a large number of products. This data is not well-suited for representing the conditions over the world and is furthermore not reflecting product-specific freight transport conditions. As the cumulative environmental impacts for several types of goods e.g. in the food sector can be demonstrated to have similar impacts compared to primary production of the food, or even exceed it substantially, it is expected that simplified approaches can significantly underestimate the relevance of freight transport for total environmental impacts of a product. Due to the positive outcome of model validation, it can furthermore be shown that using a slightly more complex but automatable freight transport model than in current LCA studies can yield much more realistic estimates of freight transport impacts and help identifying the critical levers for improving the environmental performance of a product.

Life Cycle Sustainability Assessment

Alternative food supply minimizes global environmental impacts of food system recovered from the Russia-Ukraine conflict

Sunday, 2nd July - 15:00: Footprints 1 (C0.06 KOG)

Haoran Zhang [1], ***Limin Jiao*** [1], ***Yuanchao Hu*** [1]

1. *Wuhan University*

The external interference to food system, such as regional conflict, could cause serious global food shortages. However, different ways of restoration would have distinct sustainability outcomes. Here, we developed a novel framework to examine global and regional food shortage from the Russia-Ukraine conflict, and quantify the embodied environmental impacts of disturbed and alternative food supply chain. Using this framework, we assess the distribution of food shortages from Russia-Ukraine conflict under different durations and war intensities, estimate the impact on land use and GHG emissions of the affected food trade network, and propose optimization strategies to minimize GHG emissions, land use and food transport cost. The conflict could bring 50–120 Mt shortage of nine dominant food products shortly, and cause temporal global cropland abandonment and declining greenhouse gas emissions. But the partial agricultural recovery during 2023–2024 will raise global cropland use and greenhouse gas (GHG) emissions by 9.09%–10.34% and 2.14%–3.54% (mainly in China and Europe), respectively, compared to pre-war levels. However, optimal food supply networks with free trade and prioritized agricultural expansion in higher-efficient countries could minimize food shortage and food-mile expenses, and offset cropland and GHG emissions increment by a level of those in a medium-sized country (such as the cropland use in Bangladesh and agricultural GHG emission in Argentina). Our framework is dedicated to balance food supply with GHG emissions and cropland use mitigation. Our framework also can be used to assess the possible impact of any contingency on the systems involved. Last but not least, our results underline the global and regional efforts to resist disturbance and to achieve a hunger-relieving and environmentally-sustainable food system.

Evaluating the Waste and CO2 Reduction Potential of Packaging by Reuse Model in Supermarkets in Taiwan

Sunday, 2nd July - 15:15: Footprints 1 (C0.06 KOG)

Hsin-Tien Lin [1], ***Cian-Wei Chiang*** [1]

1. *National Cheng Kung University*

Consumption of single-use packaging has been increasing globally and the waste produced causes negative impacts on both human and the environment. Retailers, such as supermarkets, developed quickly in recent years to provide for the modern lifestyle, using a lot of packaging in the process of distribution and sales. Many governments and enterprises have begun to discuss the concept of circular economy and changes in business models to completely reduce the use of plastic. 'Naked package, refill and reuse' strategy is an emerging solution. Although reuse strategies such as refilling has many potentials, the market size is still small and their feasibility in the large-scale is still unknown, this leads to concerns for the industry when considering its adoption.

This research evaluates the packaging waste and CO_2 reduction potential of 10 different products sold in supermarkets in Taiwan when adopting different reuse strategies of Reduce, Return and Refill. Weight measurement, carbon emission calculation and consumers' preference questionnaires are used to obtain data to evaluate the plastic reduction potential that can be achieved by refilling or naked packaging.

In the suggested reuse strategies, a total of 8 kilotons of packaging waste and 32kilotons of packaging CO_2 can be reduced, accounting for 50.8% and 57.3% reduction of the current situation, respectively. From the results of this research, it is suggested that retailers can propose different strategies for each product when planning packaging reduction targets. For products that have larger reduction potential, such as Fruits, Eggs and Bottled water, more ambitious strategies should be formulated. Consumers' adoption willingness of different reuse strategies is found to be high and whether they are familiar with the consumption method of the reuse strategy affects the degree of acceptance. Furthermore, the degree of acceptance is also proportional to regulations or the accessibility of the reuse strategies in retailers. For example, selling unpackaged cleansing products is an unfamiliar experience to most consumers, so it is less chosen. Experiential activities are suggested when advocating these methods, to increase consumers' familiarity with the Refill method, so as to increase their adoption willingness. Significant impacts are made with a slight change in the small proportion investigated, which suggests considerable benefits if the scope is expanded.

Redistribution does not necessarily increase emissions, overconsumption does

Sunday, 2nd July - 15:30: Footprints 1 (C0.06 KOG)

Peter-Paul Pichler [1]***, Ingram Jaccard*** [1]***, Helga Weisz*** [1]***, Johannes Többen*** [2]

1. *Potsdam Institute for Climate Impact Research (PIK),* ***2.*** *The Institute of Economic Structures Research (Gesellschaft für wirtschaftliche Strukturforschung, GWS)*

Much of the literature on carbon emissions and inequality suggests that, other things being equal, a redistribution of income from rich to poor would increase carbon emissions. A number of empirical studies have found that the marginal emission intensity of poorer households is higher than that of richer households, mainly because poorer households spend a relatively higher proportion of their income on traditionally carbon-intensive energy services. Although other studies have found conflicting evidence in some cases, we have not found a systematic discussion of the structural reasons or implications of either finding. Instead, the conventional wisdom of declining intensities is used either to quantify the inevitable environmental costs of poverty reduction or, conversely, to argue against redistributive policies on the grounds that they conflict with climate mitigation imperatives.

We analyse the distribution of carbon and energy intensities of household consumption across income deciles of European countries based on microdata and find very mixed results. While in most countries energy and emission intensities decrease with income, in some countries they remain stable or increase. We then examine the composition of consumption baskets and their respective emission and energy intensities across countries and find that one of the main determinants of the slope of intensities across income groups is the relative emission intensity of the domestic economy, in particular its energy system, compared to the average intensity of the international supply chain. Put simply, the dirtier a country's energy system is, the more its emission intensities decline with income; conversely, the cleaner its energy system is, the more its intensities rise with income. One reason for this, as suggested in previous literature, is that poorer households spend a larger share of their income on energy services such as heating or mobility, whose emissions are mostly domestic, while the share of international emissions increases with income. At least from a technical point of view, the energy sector and land-based mobility are relatively easy to decarbonise, while many of the sectors that drive up the energy and emissions intensity of rich households are much more difficult to reduce (e.g. aviation or construction), especially through domestic policies. We therefore suggest that the empirical finding of comparatively high energy and emissions intensity in low-income groups is not an obstacle to reducing inequality through redistribution or overall environmental impacts. Rather, it highlights the need for societies to invest in efficient and low-carbon energy and mobility infrastructure, while reducing difficult-to-decarbonise consumption at the top of the income distribution.

Material footprints for providing a decent standard living

Sunday, 2nd July - 15:45: Footprints 1 (C0.06 KOG)

Johan Velez [1], ***Stefan Pauliuk*** [1]

1. *Freiburg University*

The decent living standards (DLS) refers to a bundle of services which are essential to human wellbeing. The DLS is gaining momentum, primarily because it offers a simple but efficient bottom-up approach to estimate a practical minimal threshold for the energy, GHG and material consumption required to alleviate poverty. Currently, most research has been focused on estimating the energy required to provide the DLS in different social-cultural contexts. However, no attempt has been made to understand the trade-offs between the DLS and material use. Thus, we ask the following questions: firstly, what is the amount of materials, in stocks and flows, needed to provide a DLS? Secondly, which lifestyle and technology choices are effective in providing a DLS without creating excessive demand for additional materials? We integrate the existing DLS literature with the stock-flow-service nexus and the energy service cascade concepts with the life cycle assessment approach. Our results show a material footprint of 6 t/cap*year with a lower and upper bound between 2.8-13 t/cap*year is required to provide the DLS. The direct and indirect stocks required are estimated at 32 t/cap and 11 t/cap respectively. Nutrition (38%) and mobility (26%) contribute the most to the total material footprint. Buildings account for 98% of the direct stocks, while the construction sector accounts for 61% of the indirect stock. The contributions of this work are twofold. Firstly, we extend the coverage of the DLS by including the collective services dimension. Secondly, a link between the material stock-flow-services nexus and ecoinvent- LCA database is provided to compute the material footprints and in-use stocks needed to provide the DLS, previously unseen in the literature.

Keywords: Decent living standard, material footprints, process-based LCA, industrial ecology

Footprints 1

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Nexus studies

Investigating sustainable alternative sanitation systems through the lens of Water-Wastewater-Waste-Energy-Food Nexus in Chilean and Indonesian communities

Sunday, 2nd July - 15:00: Nexus studies - Oral - long format

Vanessa Bolivar Paypay [1], ***Dinar Suryandari*** [1], ***Juan Pablo Gallardo*** [2], ***Maryegli Fuss*** [1], ***Witold-Roger Poganietz*** [1]

1. Karlsruhe Institute of Technology, 2. Pontificia Universidad Católica de Valparaíso

The effects of climate change are intensifying worldwide, leading to extreme events such as droughts and floods. Countries like Chile and Indonesia are currently affected by this phenomenon, which is aggravated by their current water management systems. Since 2010, the central and north of Chile have suffered from a megadrought together with overexploitation of water sources, with societal, economic and environmental impacts. Meanwhile, the western part of Indonesia is vulnerable to flooding, significantly threatening cities' water supply, sanitation services and demanding more integrated water and wastewater management. In addition, the existing wastewater sector in both countries faces considerable challenges. Even though, most of the population in Chile has access to safe sanitation, levels of wastewater treatment in certain regions, such as Valparaíso, are still insufficient, with wastewater discharges in the ocean. Similarly, in Indonesia, wastewater is minimally treated as on-site sanitation systems are still widespread and generally only treat blackwater, while greywater is discharged untreated. These driving factors force both countries to act strategically, and the water-wastewater-waste-energy-food Nexus approach shows promise in finding alternative solutions.

Within this study, wastewater reuse is emphasized as an alternative source of water in Chile, while rainwater harvesting is highlighted as a favorable way to reduce the amount of stormwater in Indonesia. For both countries, wastewater separation into black and greywater is proposed as an alternative system. Under the Nexus concept, the blackwater is expected to be treated with organic solid waste to maximize biogas production, reducing the treatment system's energy demand. It is also expected to recover nutrients in the form of fertilizer to support food production. The greywater is reused, in the case of Chile, to increase water availability, and in the case of Indonesia, to further reduce urban runoff.

This study, a comparative analysis is carried out between the two countries to identify similarities and differences for a sustainable implementation of the Nexus concept. It is assumed that the unique characteristics of both countries lead to different requirements for implementing it, although common technical and non-technical measures could also be found. A methodological framework includes methods from system analysis (e.g., Material Flow Analysis, Life Cycle Assessment and Life Cycle Costing, Cross Impact Balance, Multi-Criteria Decision Analysis and Agent-Based Modelling) integrated into Integrative Concept of Sustainability (ICoS) of the German Helmholtz Research Association. The methodological framework brings enough content for communication and understanding in the decision-making process related to the Nexus concept by creating common-languages with local experts. For example, results show that the proposed approach is more sustainable in urban areas that are already familiar with wastewater separation. In contrast, the environmental and economic costs associated with converting existing infrastructure to an alternative system are expected to be higher. In Chile, results bring a new proposal for semi-centralized and/or decentralized plants since wastewater systems are based on large-scale centralized treatment. While enhancing the existing Indonesia's wastewater separation with an adequate treatment fosters an easier implementation of the nexus-oriented system. In the latter case, the ICoS sustainable rule "Avoiding technical risks with potentially catastrophic impacts" contributes to measure the system's resilience to floods, for example. In addition, this study includes the advantages of involving different dimensions, in this case, social, environmental, economic and political, which are usually independently assessed to broaden to other case studies.

Household energy systems in the Global South: Tracing material flows from source to service in rural Ethiopia

Sunday, 2nd July - 15:15: Nexus studies - Oral - long format

Harald Grabher [1], ***Karlheinz Erb*** [2], ***Simron Singh*** [3], ***Helmut Haberl*** [4]

1. Institute of Social Ecology (SEC), University of Natural Resouces and Life Sciences, Vienna, 2. University of Natural Resources and Life Sciences, Vienna (BOKU), 3. University of Waterloo, 4. University of Natural Resources and Life Sciences, Vienna

Biomass remains the single most important energy carrier of rural households in low- and middle-income countries (LMIC). Biomass is an ubiquitous and cheap energy source, but its indoor combustion has grave impacts on human health and its extraction is associated with negative effects on ecosystems. Yet, scientific understanding of biomass flows in rural energy systems remains incomplete; moreover, results are rarely comparable across regions because studies generally apply different system boundaries.

This paper analyses the provision of energy services of biomass in rural households from a socio-metabolic perspective. Based on a case study in rural Ethiopia, we trace biomass from source to energy services, and examine social and environmental implications. A combination of quantitative and qualitative methods is employed to better understand the socio-metabolic dynamics of domestic bioenergy in rural areas of LMIC.

We find that rural households in the investigated communities consumed on average 84 GJ/yr of biomass per household (15 GJ per capita/year). Space heating, food and drinking water preparation combined require 86% of domestic energy, with the remainder expended for hygiene, insect repellence and illumination. Improved cookstoves can reduce domestic energy use by 12%. Household responses suggest that serious environmental challenges (i.e., deforestation, erosion, soil fertility loss) related to energy provision exist. Our results indicate that most bioenergy is sourced from land also used for agriculture, including large amounts of wood fuel and grazed biomass.

Complex interactions between social, economic, and environmental factors are at play in rural energy systems. Our results open new avenues for advancing scientific understanding and integrating findings from different case studies. To assess sustainability, research needs to develop commensurate protocols to quantify energy consumption and pinpoint extraction sources to detect environmental pressures. It is essential to disaggregate domestic consumption by appliance to gauge efficiency effects. Evaluating impacts on wellbeing requires that energy consumption data be reported separately for each energy service. As families share energy, assets, appliances and services, analysing households is key. These insights are essential to advance research which promotes sustainable energy systems in rural areas of LMIC. They may also be useful to design effective interventions and foster innovations to improve provisioning of energy services.

Paving the way to circular infrastructure: Decoupling material demand from service provision in road and rail infrastructure

Sunday, 2nd July - 15:30: Nexus studies - Oral - long format

Martijn van Engelenburg [1], ***Tomer Fishman*** [2], ***Sebastiaan Deetman*** [3], ***Paul Behrens*** [4], ***Ester van der Voet*** [5]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden, 2. CML Leiden, 3. Deetman@cml.leidenuniv.nl, 4. Leiden University, CML, 5. Leiden University

The quality and size of road and rail infrastructure are crucial for development. Infrastructure In high-, middle- and low-income nations is expected to grow, driven in large part by large global investments such as the Chinese Belt and Road initiative, the US Infrastructure Investment and Jobs Act, and Europe's Global Gateway. These increases in infrastructure will require a high demand for construction materials that are often carbon-intensive and/or hard to decarbonise. Reducing infrastructure demand will mitigate emissions and overall material requirements. Exploring circular pathways in infrastructure gives a first quantification of the potential reduced demand.

Here we quantify the material stocks and flows for global road and rail networks using a dynamic material flow analysis and the services they provide to society to 2050. We use the global spatial dataset *OpenStreetMaps* which enable analysis in a high spatial resolution. We compute the current stocks of steel, concrete, bitumen, wood, copper and aggregates by type of road/rail. We then explore the potential impacts of circular strategies of lifetime extension, maintenance, lightweighting, substitution, reuse, recycling and reduce. With the combination of spatial datasets and circular scenarios, we can point out where changes to infrastructure are likely to occur. We present several counterintuitive findings from our analysis, and provide insights into virgin and secondary material demand to 2050 vis-à-vis changing transport infrastructure trends.

Stocks, Flows, Services and Practices: Nexus Approaches for Socio-metabolic Mobility Studies

Sunday, 2nd July - 15:45: Nexus studies - Oral - long format

Helmut Haberl [1], ***Doris Virág*** [1], ***Sarah Matej*** [1], ***Willi Haas*** [1], ***Barbara Smetschka*** [1], ***Dominik Wiedenhofer*** [2], ***Henrike Rau*** [3]

1. University of Natural Resources and Life Sciences, Vienna, 2. University of Natural Resources and Life Sciences, Vienna (BOKU), 3. Ludwigs-Maximilians-Universität München

Mobility requires vast amounts of resources. The mass of global transport infrastructures exceeds 300 billion tons, approximately one third of all socioeconomic material stocks. Large amounts of energy-intensive materials are required for, and accumulated in, vehicles, train carriages or airplanes. 28% of global final energy demand and 23% of the energy-related CO_2 emissions stem from the mobility system. Demand for functions such as person-km (p-km) and ton-km (t-km) is growing rapidly, and along with them resource use and GHG emissions, counteracting the deep and fast cuts in emissions required for ambitious climate targets. Whether it will be possible to address societies' need for mobility services more sustainably (i.e., at lower levels of resource use and emissions) hinges upon improved scientific understanding of the key role of mobility in both delivering services of vital importance for social wellbeing and as a 'linking practice' in everyday life.

This presentation introduces and links two innovative concepts that are useful in this context. (1) The stock-flow-service (SFS) nexus underpins studies of the systemic interrelations between biophysical stocks and flows that make up social metabolism and the services they provide to society. The SFS nexus is useful because it helps framing investigations into the wellbeing contributions of mobility such as social inclusion and participation in societal activities (work, education, etc.), healthcare and supply with products. However, the 'service' concept can be cumbersome when trying to extend 'beyond the economic' because recognition of a service entails that the entity at stake is positively valued, which raises contentious valuation issues. Moreover, services are difficult to measure. (2) The complementary stock-flow-practice (SFP) nexus draws on the growing body of practice-theoretical consumption research in the social sciences that moves beyond the individual to focus on practices as main unit of analysis. A practice is a recognizable activity pattern characterized by (a) meaning; i.e., shared understanding and valuation, (b) skills; i.e., the know-how required by a practitioner, and (c) material elements; e.g., infrastructures, tools or other biophysical elements required for a specific practice.

We present our current research applying both concepts. An analysis of the SFS nexus of personal mobility in Vienna revealed large differences between active mobility (walking, cycling), public transit and motorized individual transport regarding their requirements of material stocks and energy and their service provision. This study also helped understanding the conceptual difficulties involved in quantifying service provision. A global empirical analysis of the interrelations between mobility-related material stocks, mobility levels and social wellbeing (measured with various 'beyond-GDP' indicators) in a cross-country analysis revealed significant correlations between distances travelled and the mass of mobility-related infrastructures. Moreover, it showed that beyond certain thresholds, little, if any, additional benefit in social wellbeing is to be expected by amassing larger infrastructure stocks. We will present so far unpublished global maps of the material stocks in global mobility infrastructures, and discuss how they could be used to estimate infrastructure requirements for reaching selected sustainable development goals (SDGs). We critically examine the limitations of activity-based indicators such as p-km and t-km for measuring the delivery of services. For the SFP nexus of personal mobility, we explore potential new insights from this approach, by discussing examples of how settlement and infrastructure patterns can be expected to shape dominant mobility practices, and how these interrelations could be studied in future research.

Ecosystem Services

Creating pluralistic pathways to city-level food waste management

Sunday, 2nd July - 15:00: Social Dimensions 1 - Oral - long format

Azra Sungu [1], ***Weslynne Ashton*** [1], ***Maura Shea*** [1]

1. *Illinois Institute of Technology*

Minimizing food waste is increasingly seen as a critical strategy for addressing multiple planetary level concerns, including climate change, biodiversity loss and human food insecurity (Venkat, 2012). This strategy is often framed through an analytical approach focusing on the material flows and environmental impacts to understand current patterns and identify key indicators and opportunities for change. However, food and food waste, as a social-ecological-technological system, requires consideration of the diverse social, economic and cultural factors that govern how food is produced, distributed, consumed and discarded, if we wish to achieve sustainable transitions in this system. In addition, social equity, the fair access, distribution and use of resources for all people, has been espoused as critical for sustainability (Bozeman et al, 2023). When equity concerns are factored in, the transition of food waste management to a sustainable state, requires examining how alternative value systems and mindsets compete with the extractive ones that dominate our current systems. An intentional, values-driven alignment of stakeholders at every level of food waste prevention and management is essential to coordinating transition efforts by involving policymakers, generators, rescue organizations, processing and recycling services as well as individuals and communities. In order to achieve equitable change, the technical integration of operations and knowledge needs to be supported by a shared understanding of the systemic issue of food waste, and guided by pluralistic visions and actionable pathways for the transition in question.

This study utilizes a Design-driven collaborative sensemaking approach, alongside material flow and life cycle assessments, for facilitating stakeholder alignment in an emerging city-wide food waste management initiative. The field of Design has been advancing methods for inclusive mobilization of stakeholders in efforts towards sustainability transitions through visualization (Boehnert, 2014), co-creation (Irwin, 2018) and critical provocation (Hansson et al, 2018). We collaborated with the US Natural Resources Defense Council's Food Matters program and the City of Chicago to engage key stakeholders in a series of collaborative sensemaking activities. The activities combine design tools and frameworks such as systems mapping, Anatomy of Infrastructures (Nogueira et al, 2019), analysis of socio-technical imaginaries to combine the fragmented knowledge and perspectives of stakeholders in a visual format. We adopt a critical visualization as a means to creatively explore alignments and asymmetries between the diverse infrastructures, as well as perspectives, visions, and values through which stakeholders operate. This approach emphasizes a pluralistic framing of social-ecological-technological transitions through the lenses of diverse stakeholders to weigh social, economic and environmental goals and impacts, and activate multilevel networks to achieve these goals. The outputs from these activities are being used to help stakeholders envision, co-design and implement strategies for food waste management across silos.

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Gender and Plastics: Identifying gender issues in the plastic value chain and circular economy in the case of Korea

Sunday, 2nd July - 15:15: Social Dimensions 1 - Oral - long format

Hana Kim [1]***, Dawoon Jung*** [2]***, Munsol Ju*** [2]***, Jooyoung Park*** [3]

***1.** Korea Advanced Institute of Science and Technology,* ***2.** Korea Environment Institute,* ***3.** Seoul National University*

Just transition that leaves no one behind is an important pillar in our move toward sustainable future. Gender equality is one of the crucial elements required for just transition and in itself represents one of the UN's 17 Sustainable Development Goals (SDGs). However, global efforts for circular economy has focused mainly on economic and environmental discussions, leaving gender issues largely underexplored. Focusing on plastics, a geological indicator for the Anthropocene era, this study examines the nexus between gender and plastics from two perspectives: 1) how the production, consumption, and disposal of plastics influence gender differently, and 2) how gender plays different roles in the plastic value chain and transition to circular economy. The analysis focuses on the case of Korea because the country has proactively promoted plastic circular economy as a major plastic producer and consumer, while it shows one of the highest level of gender disparity globally.

To identify how the production, consumption, and disposal of plastics influence gender, we evaluate the gender composition of workers and gender-disaggregated impacts of the working environment (e.g., physical hazards and risks, accidents, diseases) in three major sectors of the plastic value chain: chemicals and chemical products, rubber and plastics, and waste management. In addition to the working environment, the health impacts of plastic additives are investigated from the literature. Plastic additives such as bisphenol and phthalate can impact women and men differently, according to varying biological responses to hazards and the level of exposure which is gender-dependent. As for the gender roles during consumption, we investigate gender-specific patterns of consumption behavior by analyzing various survey results, such as on green consumption and time use. Finally, to understand the roles of women and men in circular economy transition, we analyze circular economy cases for multinational corporations, start-ups, activists, and policy decision-makers and the gender composition of each case. Improved understanding of the gender-plastic nexus would contribute to exploring ways to achieve gender equality in the plastic value chain and to empower women and men for its circular economy transition.

Integrating sustainable development objectives into Official Development Assistance: Exploring the effectiveness of French ODA in Vietnam to strengthen the country's capacity to adapt to and mitigate climate change

Sunday, 2nd July - 15:30: Social Dimensions 1 - Oral - long format

Margaux DUHEM [1], *Masachika Suzuki* [1]

1. Sophia University

The Official Development Assistance (ODA) is the financial assistance provided by developed countries to low-income and lower-middle-income countries. Growing awareness of climate change and warning from scientists against the consequences have made climate change a major concern for bilateral and multilateral development agencies in their operations. The Sustainable Development Goals (SDGs) promoting just and equitable development for all not only suggests to redefine the objectives of the ODA, but also to reconsider its functioning, operation, and management.

This research examines how the Agence Française de Développement (AFD), France's main public agency managing the ODA, incorporates the SDGs into its aid system for countries at the frontline of environmental, social and health disasters being caused by climate change. A case study is conducted in Vietnam where the AFD has been operating since 1994 as one of the key bilateral ODA donors. The AFD has also carried out research on environmental issues specific to the Mekong region in order to increase the effectiveness of its aid in the fight against climate change. While the alignment of the ODA with the SDGs is promising news, the ODA has been still the subject of much criticism among researchers and scholars who denounce the risks of indebtedness for countries receiving aid and the asymmetrical relationships that aid tends to create between donors and recipients. Although the AFD recognizes the limits of development aid, the ODA could take an instrumental role in supporting the country in its efforts to achieve the SDGs.

The hypothesis of this research is that the systematic use of the SDGs in the ex-ante and ex-post evaluations of projects financed by French ODA can increase the impacts of the projects in the field of sustainable development. Moreover, innovative approaches taken by the AFD could provide useful lessons applicable for other bilateral and multilateral development agencies. Based on AFD evaluation documents and interviews with AFD staff in France and Vietnam, this study highlights the integration of the SDGs into the evaluation system set up by AFD. The initial results of this study show that while the direction taken by the AFD is promising, the late consideration of the SDGs, combined with the lack of precise indicators to quantify the results of a project, makes it difficult to affirm the effectiveness of aid in the holistic social, economic, and environmental landscape. The main recommendation of this study is to strengthen ex-post assessment of projects in such a holistic landscape. In addition, AFD's positive attitudes towards multilateral cooperation with other donors, especially in Vietnam, could help spread its model and thus contribute to a more systematic consideration of the SDGs by development agencies.

Key words: *ODA, SDGs, AFD, Vietnam, Climate Change*

Sharing and consuming in space – what is important to know for the planning of a Sharing City?

Sunday, 2nd July - 15:45: Social Dimensions 1 - Oral - long format

Divia Jimenez Encarnacion [1], ***Leonardo Rosado*** [1], ***Liane Thuvander*** [1]

1. *Chalmers University of Technology*

Cities are responsible for approximately 80% of resource use and 75% of greenhouse gas emissions. In particular, household products represent over three fifths of the impacts of consumption for the total life cycle. A transition in how households consume is necessary - from private purchasing, use or storage, and disposal of products; towards more circular models such as using rather than owning.

The sharing economy (SE) is gaining recognition as a way to increase circularity at the household level, by presenting the opportunity to prevent the purchase of new items by utilizing products that are already available elsewhere. Through the SE, products' capacities could be fully tapped, and a more efficient use of resources could be made. "Sharing cities," such as Amsterdam and Seoul, have recognized the potential of the SE to address their sustainability goals, and integrated its concepts within their urban planning. However, the proactive approach of these cities is an exception. The growth of the SE phenomenon has been largely driven by private companies such as Uber, while local governments have often reacted to the challenges that can emerge from the SE rather than planning it. As such, it has been less likely for cities to derive environmental benefits from the SE. Urban planning can therefore play a significant role in leveraging the environmental benefits of the SE. To support a thriving SE in cities, spatial data could provide key information for the urban planning. Sánchez-Vergara et al. highlight that the concept of "place" is a key factor in the performance of sharing, similar to the results of a recent survey in Gothenburg, Sweden which indicate that the location of sharing initiatives (SIs) is the main aspect that citizens consider before sharing. Demailly et al. also mention that the geographical scale at which sharing occurs influences the amount of subsequent environmental impacts. As a response, this study aims to identify spatial information to aid local governments in the planning of environmentally sustainable "sharing cities." We adopt Gothenburg as a case and focus on generating data that describes how consumption and sharing take place throughout the city. To understand the patterns as locally as possible, the data is studied at the neighborhood level.

Preliminary results have been obtained through desk research. The data sources identified include two cross-sectional questionnaire surveys regarding the SE, conducted for Gothenburg in 2021; and the National Household Budget Survey 2022, which contains purchase data for Swedish inhabitants. Variables in the surveys cover over 60 shareable products and 7 socio-economic characteristics such as age, gender, income, education level, dwelling type, and household composition. Spatial data regarding the built environment are retrieved from "OpenStreetMap" and a local map that collects SIs within Gothenburg ("SmartaKartan"). Data from the surveys will be combined with spatial data throughUrban Material Flow Analysis, statistical analysis and geographic information systems.

The following is an example of the insights that can result from the analysis: Neighborhoods in the central districts in Gothenburg show potential for further action regarding the sharing economy. The central neighborhoods present the highest perception of owning too many household products, and the most positive attitudes towards diverse sharing actions. Conveniently, this is also where the highest density of SE initiatives is seen, so dissemination of information about the SIs might be crucial to ensure their utilization.

Social Dimensions 1

Creating pluralistic pathways to city-level food waste management

Sunday, 2nd July - 15:00: Social Dimensions 1 (B0.13 KOG)

Azra Sungu [1]***, Weslynne Ashton*** [1]***, Maura Shea*** [1]

1. *Illinois Institute of Technology*

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Special Session: Plastics, Chemicals and Sustainability (Part 1)

Planet compatible pathways for transitioning the global chemical industry

Sunday, 2nd July - 15:00: Special Session: Plastics, Chemicals and Sustainability (Part 1) (B0.41 KOG)

Fanran Meng [1], *Jonathan Cullen* [1]
1. University of Cambridge

The modern chemical industry, which makes plastics, solvents, and fertilisers, stands at a crossroads. Following decades of fast-paced growth, chemicals and their derivatives are now ubiquitous in society and essential for supporting modern lifestyles, contributing over 7% of global GDP in 2017. Moreover, in the future, chemicals will likely play a significant role in delivering net-zero targets (e.g. ammonia for shipping). However, energy-intensive chemical production processes were responsible for 14% of global oil and 9% of global gas consumption and released 13% of global industrial direct CO_2 emissions in 2020. This industry presents multiple threats to the planetary boundaries that will undermine its value proposition and license to operate, requiring major system transformation.

Our study aims to identify and outline the key conditions for the chemical industry to reach net-zero greenhouse gas emissions along planet-compatible pathways between 2020 and 2050. Emissions from feedstock sourcing, production, use phase, and end-of-life treatments are considered. We present seven planet-compatible chemical pathways towards 2050 employing demand-side and supply-side interventions with cumulative total investment costs of US$1.2-3.7 trillion. Resource efficiency and circularity strategies reduce demand for chemicals by 23-33% and are critical to mitigate the supply risks associated with using fossil and biogenic feedstocks and the scale-up challenges for technologies like carbon capture and storage.

Achieving net-zero emissions across the lifecycle stages for chemical products is possible. Shifting carbon sources from ground to air (fossil to biogenic, air-capture) and carbon destinations from air to ground (emissions to sequestration) would enable net negative emissions, safely returning 0.5 gigaton CO_{2eq} to the ground every year across non-ammonia chemicals, while still providing essential chemical-based services to society. The chemical industry should accelerate the development of technologies highlighted in this study (non-fossil feedstocks, carbon capture and storage, methanol-to-olefin/propylene and methanol-to-aromatics), and collaborate with other industries to drive resource efficiency and material circularity, reduce demand, and balance the carbon flows.

Mapping the greenhouse gas emissions of petrochemical production

Sunday, 2nd July - 15:15: Special Session: Plastics, Chemicals and Sustainability (Part 1) (B0.41 KOG)

Fanran Meng [1] **,** ***Luke Cullen*** [1] **,** ***Jonathan Cullen*** [1]

1. *University of Cambridge*

In recent years, demand for petrochemical products has soared. Today, the global petrochemical sector makes nearly 1 billion tonnes of chemical products, including 420 Mt of plastic products, 290 Mt of nitrogen fertilisers, fibre, and rubber, and 250 Mt of other products such as solvents, additives, and explosives. The petrochemical sector is responsible for 30% of final industrial energy use, including 11% of global oil demand and 10% of global natural gas demand, and releases 17% of global industrial Greenhouse Gas (GHG) emissions.

Despite the impetus for large-scale action to reduce GHG emissions to counter climate change, it is often unclear which products and materials in the petrochemical sector are the most emissions-intensive, which undermines policymaking efforts in this sector. Accurate GHG emission profiles improve climate change mitigation strategies and are needed in the petrochemical industry.

Production emissions arise from four life-cycle stages: upstream raw material extraction and processing including fugitive emissions; upstream energy conversion in the energy sector (indirect utilities); on-site energy conversion (direct utilities); direct process emissions resulting from chemical reactions and high-temperature heat generation. Beyond production, emissions are released from the use phase of some petrochemicals (e.g. fertilisers) and from end-of-life product treatment. Significant environmental impacts also occur from sources other than GHGs, including fertiliser run-off contributing to eutrophication, bioaccumulation of toxic chemicals in organisms, and plastic waste in the world's oceans harming sea life.

This study presents past, current, and projected GHG emissions of chemicals and plastics using life-cycle analysis broken down across six key dimensions: product, region, year, gas type, life-cycle stage, and uncertainty. The underlying structure of the complex chemicals production system is mapped and built into an updateable framework and interactive tool using a novel material flow analysis methodology. The mass flow mapping methodology aggregates processes and objects according to a semantic skeleton, which enables the visualisation of results at different levels of detail. We then build the life cycle assessment model to infer chemical production emissions based on emission intensity factors, which we calculate using a mass allocation from product recipe databases. Our production technology-specific emission intensities for each chemical are compared to those reported in existing life cycle assessment databases such as ecoinvent and Carbon Minds. The absolute production emissions of chemicals are estimated by multiplying the emission intensity factors with production and consumption data.

We find that the GHG emissions of global petrochemical production were 2.91 billion tonnes CO_{2eq} in 2020 and are expected to reach 6.99 billion tonnes CO_{2eq} in 2050 following current trends. North East Asia remains the largest emitter across all regions: 1.55 billion tonnes CO_{2eq} or 53% of the total emissions in 2020 and 2.84 billion tonnes CO_{2eq} or 40% of the total emissions in 2050, respectively). South Asia sees a large increase from 0.44 billion tonnes CO_{2eq} in 2020 to 3.83 billion tonnes CO_{2eq} in 2050. The interactive tool is accessible to a wide range of users and provides informative breakdowns for policymakers. The tool could help assess the environmental impacts of different production routes towards low-carbon solutions.

How consistent and complete is data on the global petrochemicals sector's emissions?

Sunday, 2nd July - 15:25: Special Session: Plastics, Chemicals and Sustainability (Part 1) (B0.41 KOG)

Rick Lupton [1], *Georgie Wellock* [1], *Stephen Boyle* [1], *Fanran Meng* [2], *Luke Cullen* [2], *Jonathan Cullen* [2], *Dominika Malkowska* [1]

1. University of Bath, 2. University of Cambridge

The petrochemical sector is estimated to account for a third of industrial energy use and almost a fifth of global industrial CO_2 emissions. Demand for chemicals is expected to double by 2050, which will place further strain on the environment. Good data to monitor these emissions is important, but difficult because they occur at many supply chain stages (e.g. fugitive emissions from natural gas production, process emissions, utilities, during use of fertilisers, and from end-of-life processing of plastics), and occur in complex supply chains distributed around the world, with different reporting frameworks applied to different parts. Even the impressive efforts of global datasets such as the UNFCCC emissions reporting [1] result in data with gaps, and incompatible classifications and definitions. Other datasets contribute more detail, but with limited scope, and their own classifications. Some of these are behind expensive paywalls, such as the detailed ICIS Supply & Demand chemical sector data [2]. While there have been qualitative assessments of such global data [3], the level of consistency and completeness of global data about petrochemical emissions data has not been quantified.

In this study, we use data integration methods [4] to bring together multiple freely-available and commercial data sources in a consistent framework to enable comparisons to be made. To do this, we define a hierarchical structure of petrochemical processes and material types, which can be used as the scaffolding to connect different datasets, and define the correspondence tables to map to this common structure and infer new quantified data points. We use this combined dataset to highlight gaps in the global data, check for consistency and variation, and assess the uncertainty in total global petrochemical emissions based on these sources. The results show that there are some emissions associated with petrochemicals globally which are not well covered by available data, and highlight some limitations of global UNFCCC datasets when used to understand the petrochemicals sector, such as variations in how activity data is reported. By making use of detailed commercial datasets reporting at the plant level, the results allow for a level of cross-checking that is not possible with only freely-available data.

References: [1] UNFCCC Greenhouse Gas Inventory data. https://unfccc.int/ [2] ICIS Supply and Demand database. https://www.icis.com/explore/services/supply-and-demand-database/ [3] Cullen et al (2022): Carbon Clarity in the Global Petrochemical Supply Chain: A Critical Review. https://www.c-thru.org/first-year-report/ [4] Germano et al (2021): Use of semantic technologies to inform progress toward zero-carbon economy. Lecture Notes in Computer Science. DOI: 10.1007/978-3-030-88361-4_39

The Scope of Change for a Circular and Low Carbon Petrochemical Sector in the Context of Economy-wide Energy and Material Flow Analysis

Sunday, 2nd July - 15:35: Special Session: Plastics, Chemicals and Sustainability (Part 1) (B0.41 KOG)

Carey King [1]***, Neeraj Hanumante*** [1]

1. *University of Texas at Austin*

To effectively model the relationships between energy and economic outcomes (e.g., gross domestic product, employment, wages, and debt) it is useful to have economic frameworks that consistently merge the physical, energetic, and financial perspectives of the economy within a dynamic macroeconomic growth model. To date, many macroeconomic models calibrate themselves to various environmental, mass, and energy stocks and flows. However, few of these economic approaches are also stock and flow consistent in monetary terms. The Human and Resources with MONEY (HARMONEY) model provides one framework to maintain full consistency. It uses an input-output structure and is stock and flow consistent in money, energy, and mass using a post-Keynesian monetary accounting framework and biophysical and ecological economics principles [King (2020, 2022)].

One research goal is to provide a replicable method to calibrate macroeconomic growth models, such as HARMONEY, to country economies by blending research and data from industrial ecology, energy analysis, and economics. In addition, including this information into macroeconomic models will help inform studies of the dynamic feedbacks during a low-carbon energy transitions and of economic metabolism.

This presentation summarizes the results from calibrating the HARMONEY model framework to the United States economy divided into six productive sectors, one of which is petrochemical production, plus the household and government sectors. Each sector has the following properties that we will summarize: the mass stock accumulated in its capital (e.g., buildings, vehicles, petrochemical manufacturing facilities), mass inflows and outflows, and energy inflows and outflows. Using data from Streeck et al. (2021), EXIOBASE3 [Stadler et al., 2018], the International Energy Agency, and the U.S. government, we estimate these stocks and flows for metals, fossil fuels, biomass, non-metals such as concrete and aggregate, and plastics.

Example results from calibrating to U.S. using data sources near the year 2015 are as follows. We have allocated approximately 100 gigatonnes of mass stock in the U.S. economy among fifteen categories of capital, such as roads, buildings, and power plants. HARMONEY models the energy consumption, as fuel, for each type of capital, and we summarize that calibration procedure for the approximately 100 exajoules per year of primary energy consumption of coal, natural gas, oil and refined products, and primary electricity. From these calibrations, we estimate the annual direct energy consumption per mass (MJ/year/kg) of each type of capital ranges from approximately 0.4 for pipelines, 1-2 for homes and commercial buildings, 40-100 for road vehicles, and about 100-300 as dissipated electricity in the transmission and distribution grid.

In our calibration we specify a petrochemical sector. Our presentation will summarize the current the level of capital infrastructure (as mass and money valuation) and energy and mass flows associated with petrochemical production. We use this as context for future simulations of a US-based HARMONEY model for estimating the level of investment and changes to flows of mass and energy associated with decarbonizing a large portion of the petrochemical sector (e.g., ammonia production, plastics production) and recycling of plastics.

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Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1)

A large-N analysis of Circular Economy policy accumulation in China from 2006 to 2020

Sunday, 2nd July - 15:00: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

Wenting Ma [1], ***Thomas Hoppe*** [2], ***Martin de Jong*** [3]

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In response to the mounting environmental problems in recent years, the circular economy (CE) has become a popular policy concept in China. China's national government has proposed and implemented a series of policies to achieve CE goals. Over the last fifteen years this led to "policy accumulation". The question can be raised what CE policy accumulation looked like in terms of policy, goals and instruments used. To study this phenomenon, this paper presents national government CE policies for the timespan 2006 – 2020. A systematic review and analysis of policy documents was conducted. Results show that after a stable period with limited growth in the 11th (2005-2010) and 12th (2010-2015) Five-Year Plan periods (FYP), the central government issued more and more CE policies during the 13th FYP (2016-2020) period. CE policy goals experienced a shift in focus from improving production efficiency via lowering of consumption patterns, to embracing a whole life cycle perspective. CE policy instruments moved from predominantly economic instruments in the 11th and 12th FYPs to regulatory instruments along with communicative and network instruments in the 13th FYP. The paper also discusses the driving factors for CE policy accumulation and ends with suggestions for future study.

Promote the deep decarbonization development of Eco-Industrial Parks in China by considering the GHG emissions structures and characters

Sunday, 2nd July - 15:08: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

LU SUN [1], ***Fufu Wang*** [1]

1. *Xi'an Jiaotong University*

The rapid industrialization process has brought many severe problems such as a shortage of natural resources, environmental pollution, and greenhouse gas emissions in China. China has proposed the goals of carbon peaking and carbon neutrality target in 2020 to mitigate climate change. Eco-industrial parks (EIPs) are the main platform of energy consumption and the main source of greenhouse gas emissions in China. The deep decarbonization development of EIPs is vitally important to contribute to the realization of China's dual carbon goals. This study selected four different types of national eco-industrial parks in China to investigate the GHG emissions reduction potential and optimization path in the future. Firstly, we built the GHG emissions inventories and databases of four different eco-industrial parks in Ningbo, Shanghai, Xi'an, and Guigang city; Secondly, we construct an integrated model to predict the peak of carbon emissions and explore the main contributors of the four EIPs; Finally, the deep decarbonization paths optimization of different eco-industrial parks with different industrial characteristics are proposed. This study explores the paths of deep decarbonization development of different industrial parks under the constraints of dual carbon targets, which shows a demonstration for China and other developing countries in the rapid industrialization process to achieve the goal of carbon peaking in eco-industrial parks.

New Business Models in Post-Consumer Recycling in Urban China

Sunday, 2nd July - 15:16: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

Xin Tong [1]

1. Peking University

The innovation in business models for post-consumer recycling is booing in cities of China in recent years. This chapter illustrates the emerging business models for post-consumer recycling in urban China facilitated by the Internet technology. We identify three categories of emerging models: (1) community-based programs targeting the garbage sorting behavior of consumers for all household waste, (2) reverse logistic systems with automatic vending machines attached to traditional commercial chains, and (3) pure internet solutions to bridge the transactions between the consumers and recyclers. All these business models share the common characteristics that they use internet technology, which is aggressively promoted in China as “Internet +” by both government policies and venture capital investment. The various business models serve as the link between the firm and the system level and reflect the diverse possibilities for the future evolution of the recycling system in China. Five elements are keys to the success of the business models, including convenience for consumers, traceability for producers, profitability for recyclers, hybridity for collection, and reliability of the information used by the public to address the various values pursued by different actors involved in the recycling chains. The results reveal the dilemmas facing each business model in balancing among all the elements and highlight the governance challenge of integrating the EPR scheme with the municipal waste management system.

Analysis of efficient waste transportation methods to enable incineration heat supply to Japan's chemical industry

Sunday, 2nd July - 15:24: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

Makiko Doi [1]***, Katsuhiko YOSHIKAWA*** [1]***, Takashi Tsubouti*** [1]***, Masaki Murakami*** [2]***, Toshiro Bandai*** [2]***,***
Keitaro Ikeda [3]***, Toshiki Kitai*** [3]***, Minoru Fujii*** [4]

1. *EX Research Institute Ltd.,* ***2.*** *NIPPON EXPRESS CO., LTD,* ***3.*** *GUUN Co.,Ltd.,* ***4.*** *National Institute for Environmental Studies*

The operation of a waste to energy (WtE) facility (producing steam and electric power) that exploits economies of scale, at an industrial level, will be advantageous in realising a decarbonised society. To achieve this, it is essential to improve the efficiency of waste transportation by expanding the area of waste collection and using combined transportation. In Japan there are approximately 1,000 incineration facilities, including large and small, used for household waste. Presently, with efforts to expand the waste transportation area, the average facility waste production is 167 t/day (in the 2021 financial year). Approximately 36.6% (386) of the total number of facilities have power generation functionality, and 90 facilities (less than 10% of the total) supply steam to the nearby factories. Therefore, there remains significant scope for the heat generated by incineration to be effectively utilised in Japan.

For instance, it has been calculated that transitioning from the current system of eight 100 t/day incineration facilities to a new system with 800 t/day incineration facilities can yield a 20 t of waste value of approximately 570,000 yen. If the transportation cost is less than this amount, the business would benefit economically. Through information from public surveys and site visits, we investigated efficient waste transport methods employed in Europe and Japan. We found that, in Europe, many waste treatment facilities that process more than 1,000 t/day of waste have been established in major regions. We identified several cases where these facilities supply steam to surrounding factories. Further, there is not included kitchen waste in the combustible waste. Moreover, they have optimally combined all transportation methods, such as relay, railroad, truck, and ship, to expand the waste collection range and improve efficiency.

In Japan, national notifications for widening of the area for waste treatment were issued in 1997 and 2019, and these have resulted in gradual improvement. Achieving wide-area waste collection and transport is affected by several factors, including stakeholder's participation. These factors are the procurement of land for the development of large-scale incineration facilities, consolidation of plans for facilities with different renewal periods, and the avoidance of loss of employment opportunities due to business conversion. Transfer facilities have been established to expand the transportation area; However, these show gradual development as a result of the progress of regional expansion based on conceptual planning. These mean, It is not necessarily addressed as a specific goal to develop a transport system for the decarbonization of the materials industry with WtE facilities. It is expected that the development of a waste transformation system with stakeholder's participation will enable steam from waste incineration to be supplied to the chemical industry. If these facilities will have realized, will have increased future scope to introduce carbon capture utilisation (CCU) functionality to municipal waste from incineration facilities. We will report our investigation on Efficient transportation system.

An evolutionary institutional framework to evaluate circular economy performance: Empirical findings from China and Hong Kong

Sunday, 2nd July - 15:32: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

Benjamin Steuer [1]

1. The Hong Kong University of Science and Technology

Over the past two decades, the circular economy (CE) has gained in traction globally. Governments in China, Japan and EU member states have identified the concept's value: Be that as a strategy to improve resource efficiency and conservation, to tackle material scarcities, or more recently to mitigate climate change impacts and progress towards sustainable development. Similarly, corporate stakeholders from multinationals to small-and-medium sized firms engage in circular business model innovations to tackle price hikes for materials and explore new consumer niches. Likewise, citizens around the globe are increasingly alarmed by rising temperatures, anthropogenic environmental calamities and self-created waste volumes, inducing them to change or adjust consumption habits and preferences.

The result of these efforts from different stakeholders has induced an emergence of new rules, business operations, and organised as well as spontaneous behavioural routines. In respect to the CE, these institutions – systems of rules that structure behaviour and interaction of stakeholders (Groenewegen et al., 2010) – are often encapsulated in R-principle practices, such as 'refuse', 'rethink', 'reduce', 'reuse', 'recycle' etc. That is to say, socio-economic systems feature growing numbers of circularity rules, which require stakeholders to behave in a certain way for realising CE specific goals. Take the variety of globally institutionalised regulatory, behavioural and corporate strategies towards zero-plastics as case in point.

Against this background, the central question is why and under which conditions CE related institutions perform effectively. In search of a response, this contribution will present an analytical framework that is rooted in the evolutionary institutional economics and applied to assess CE case studies. It combines a problem-solution-problem causality with a generalised Darwinian perspective on rule-system change, which takes the dynamics of contesting stakeholder interests into account. To verify the viability of the analytical framework, two hypotheses on effectiveness are tested against empirical data from field research, stakeholder surveys as well as general opinion surveys conducted by the author. In terms of regional and research content focus, the assessment will focus on cases from mainland China and the Hong Kong SAR. Thematically the presentation revolves around household waste management, PET bottle recycling and circular business model innovation.

As for findings, some key take-aways of the framework's evaluation of CE institutions in Hong Kong and China are: 1. Rule-systems that provide for a high degree of stakeholder interest inclusiveness are more effective in terms of practice proliferated and quantitative performance than those that exclusively focus on (quantitative/ indicator-based) outputs or benchmarks. 2. Capturing information feedback from stakeholder preferences and activities are key to innovate and adapt institutions in a manner that their efficiency is raised over an evolutionary timeline. 3. Effective, i.e. quantitatively well performing CE institutions in mainland China and Hong Kong are less found among the top-down issued, official rules, but rather those that emerge bottom-up crafted by non-state/ self-organised stakeholder groups.

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Combining woody and waste biomass use for innovative urban symbiosis

Sunday, 2nd July - 15:40: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

Satoshi Ohnishi [1], ***Hidetoshi Kuramochi*** [2], ***Takuro Kobayashi*** [2], ***Shogo Nakamura*** [1], ***Minoru Fujii*** [1], ***Kei Gomi*** [1]

1. National Institute for Environmental Studies, 2. Material Cycles Division, National Institute for Environmental Studies

Decarbonizing the industrial sector is "hard-to-abate", and utilizing renewable biomass is a candidate to achieve a reduction of Greenhouse Gas (GHG). Energy-intensive industries located in large industrial parks need innovative technology development and capital investment, such as hydrogen reduction in blast furnaces and large-scale CCUS, in addition to the large-scale circular symbiosis in petrochemical complexes. On the other hand, small- and medium-scale industrial parks aim to find another solution for decarbonization because vast numbers of factories are located in comparison with large industrial complexes. One of the most promising options is renewable biomass with geographical proximity to industrial parks. In urban symbiosis, utilizing biomass on a regional scale positively impacts on local economy and society in addition to GHG reduction. Previous studies have discussed woody and waste biomass separately. Several cases of the use of woody biomass in industrial parks with paper mills have been reported as industrial symbiosis. Other cases with methane fermentation systems using wet biomass are in urban areas including power generation and heat recovery as urban symbiosis. Reviewing industrial and urban symbiosis, combining woody and waste biomass use could provide a new research topic for innovative circular solutions.

Therefore, based on the past industrial and urban symbiosis progress, we propose a combined system of woody and wet waste biomass and discuss its concept, feasibility, and effectiveness. Specifically, by designing a system in which woody biomass CHP and methane fermentation are constructed with the same site to improve the efficiency of their respective material and energy flows, and in which waste heat is for producing steam in a wood chip boiler for industrial process. We evaluate the cost and GHG reduction of the systems and discuss how the systems can contribute to decarbonization in a small to medium-sized industrial complex.

This study presents a method for estimating energy demand by making assumptions about the types and sizes of factories located in industrial parks for policymakers considering strategies for attracting factories that aim to decarbonize. After estimating energy demand, the energy supply system will be defined to match the demand accordingly. A combined system of woody and wet waste biomass decarbonizes small and medium size industrial complexes to provide a utility system as renewable energy. Finally, we discuss appropriate symbiotic boundaries depending on regionality, characteristics of the waste/by-product, and biomass.

Development classification Model of Demand-Place Industries by Text Analysis Using Company Names and Estimated of Spatial Heat Supply Potential from Waste for Circular Economical Potential Evaluation -Case Study on Steam Supply-

Sunday, 2nd July - 15:48: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 1) (A0.51 KOG)

Seiya Maki [1], Satoshi Ohnishi [1], Minoru Fujii [1], Naohiro Goto [2]

1. National Institute for Environmental Studies, 2. Toyo University

The establishment of Circular Economy is required in the field of waste management. The supply of extracted steam from waste treatment plants (WTPs) to neighboring factories is expected to be one of the efficient circular resource uses. However, the composition of the waste to be supplied as a circular resource is not spatially understood. Therefore, it has not been estimated what kind of plant location would be economically and environmentally efficient. On the other hand, the available amount of recyclable resources such as steam for factories are difference depending on the type of industries. However, industrial location for each industry type has not been compiled in the form of statistics. In this study, we estimated the circular resources demand potential from industrial locations and supply potential from waste for the use of steam from waste. Based on these results, we evaluated the potential for steam utilization based on spatial analysis. Estimating the spatial distribution of waste, we used household consumption data for 1 km mesh and waste composition information provided in the WTP. And we developed waste transportation process model to estimate the amount of waste generated per unit of household consumption. We focused on including characteristic word of company names in each industrial sector. Using the company names as text data, we estimated the spatial demand for steam by classifying target factories for steam supply by the LSTM method based on company names in Factories Static Book and Telephone Number Book data. As these results, we examined the possibility of supply and demand matching using steam as an example.

Special Session: Applications of Machine Learning and Data Science in Industrial Ecology

Generating Life Cycle Inventory for Industrial Systems in Developing Countries with Graph Neural Network: A Case Study on Electricity Production

Sunday, 2nd July - 16:30: Special Session: Applications of Machine Learning and Data Science in Industrial Ecology (A0.51 KOG)

Hannah Wang [1], ***Yuan Yao*** [2]

1. *Yale University,* ***2.*** *Center for Industrial Ecology, Yale School of the Environment, Yale University*

Developing countries have become vulnerable areas of global environmental and resource challenges [1]. Due to the lack of life cycle inventory (LCI) for products, services, and industrial systems, it is often difficult to conduct robust life cycle assessments (LCA) for developing countries to empower optimization for sustainable operations [2]. Many LCA studies for products or systems in developing countries were based on LCI from developed countries; as a result, uncertainties exist when leveraging developed countries' data to evaluate developing countries' situations [3]. It is indispensable to fill the LCI data gap to reduce uncertainty. Approaches to impute missing LCI data have previously been reviewed by Zargar et al.[4], among which none have attempted to generate geographic-dependent LCI with data-driven methods.

To address the research gap, we applied the graph neural network theory to estimate geographic-dependent LCI for (developing) countries that lack data. As a proof of concept, this talk will present a case study on electricity production systems. Our method consists of three components: (1) a graph network that is a digital-twin representation of production system similarity, where each node in the network is a system uniquely identified by its production location, location-specific socioeconomic information, and product subtype (in this case, the product is electricity; product subtype includes different types of electricity, e.g., wind, hydro, solar power). Nodes are connected if their LCI records are similar; (2) graph neural network algorithms that train the graph representation. The resulting graph model identifies the top 5 similar systems for any given system of interest with location and product subtype information; (3) aggregation of the top 5 systems' LCI to predict LCI for the system of interest.

The talk will present the electricity production LCI estimated by the top 5 similar systems predicted by Graph Neural Network. This method is expected to be easily generalized to any production systems that differ by geography or subtypes, e.g., crop production, biomass production, and chemical production. For a system that lacks LCI, given its geographic, socioeconomic, and technological data, our method can identify systems with the highest similarities worldwide and predict the LCI for this system of interest. To this end, our LCI imputation approach will support robust geographic-dependent LCA, especially in assisting decision-making regarding sustainable industrial systems in developing countries.

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Machine learning for prediction of life cycle inventory data: Exploring opportunities and challenges using a case study of the Canadian egg industry

Sunday, 2nd July - 16:45: Special Session: Applications of Machine Learning and Data Science in Industrial Ecology (A0.51 KOG)

Ian Turner [1], *Nathan Pelletier* [1]

1. The University of British Columbia

For inclusion in proposed special session *Applications of machine learning and data science in industrial ecology*

Environmental life cycle assessment (LCA) is a systems-level modeling approach for holistic assessment of the cumulative resource demands and environmental impacts of a product or service throughout its supply chain. To perform an LCA, life cycle inventory (LCI) data characterizing relevant resource and material inputs and outputs must be collected for all relevant foreground processes in the system model[1,2]. Collection of high-quality, representative data is of the utmost importance to ensure the robustness of generated LCA models, and the conclusions drawn from them[3]. Data collection may, however, be resource-intensive, and face other limitations such as survey non-response which may result in collection of insufficient data to generate a representative model[4]. Additionally, when studies aim to assess specific sustainability interventions, representative data may be unavailable, requiring that LCI data instead be collected from small scale pilot-studies, or extrapolated based on specific assumptions[5,6]. Machine-learning based predictive modeling represents a potential solution for filling data gaps, or generating novel LCI data. Incorporation of predictive models into LCI data collection processes may allow for generation of more robust LCA models, particularly for prospective analyses of proposed sustainability improvement interventions. Development of predictive models may, however, be hindered by a number of different challenges, including small or uneven samples, data gaps, choice of appropriate predictive framework, uncertainty associated with predictions, and others.

Using a case study of the use of machine learning models to predict novel LCI data for characterizing increased lay cycle length in the Canadian egg industry, opportunities and challenges, as well as strategies for overcoming them, were explored. In Canada, lay cycles average approximately one year in length[7], relatively shorter than many countries elsewhere[8–11]. Increasing productivity per hen placed, by lengthening lay cycle lengths, may be an effective strategy for improving sustainability outcomes in the Canadian egg industry[10,12], provided that resource-use efficiency remains sufficiently high. Using a primary data set collected via surveys of Canadian egg farmers and U.S. egg farmers operating longer cycle lengths, models were developed for the prediction of resource use on Canadian egg farms under extended lay cycle scenarios. Missing data from survey non-response was imputed using the MissForest algorithm, a random-forest based imputation method[13]. Issues related to data imbalance were mitigated using synthetic minority oversampling with Gaussian noise[14], and different predictive frameworks were implemented for different inventory datum, including polynomial regression, and random forest. Models were fit with varying degrees of success across different inventory data, and sensitivity analyses were proposed as a method for assessing the prediction uncertainty throughout an LCA model. The generated data will subsequently be used to support assessment of the sustainability impacts of potentially extending lay cycles in the Canadian egg industry. Overall, the use of predictive models represents a promising source of data that should be explored further by LCA practitioners in all fields.

Predict chemical environmental impact using machine learning methods

Sunday, 2nd July - 17:00: Special Session: Applications of Machine Learning and Data Science in Industrial Ecology (A0.51 KOG)

Chao-Hsu Yang [1], *Zih-Ee Lin* [1], *Pei-Te Chiueh* [1]
1. *National Taiwan University*

The rapid increase in the number of new chemicals presents a challenge in understanding their life-cycle impacts due to the missing data of their manufacturing process in current life-cycle inventories (LCI) databases. Hence, it is important to develop a method that could instantly predict the environmental impact of these chemicals' productions, and one such method is using the Quantitative Structure-Activity Relationship (QSAR) model. However, the applicability domain of the QSAR model is mainly limited to organic molecules since the available data and molecular descriptors are primarily focused on organic molecule calculations. Therefore, it is necessary to explore other methods for developing a model that is suitable for both organic and inorganic chemicals.
In this study, we introduce a machine learning model that estimates environmental impacts for both inorganic and organic chemicals' productions. The model used the chemicals' electrical configuration as descriptors and ten midpoint impact categories of damage to ecosystems in ReCiPe2016. The model results show relatively higher performance in predicting freshwater ecotoxicity and marine ecotoxicity, with testing data R2 values of 0.828 and 0.841, respectively. We also discovered several important features that could highly affect the upon mentioned environmental impacts.
Further research is required to fully validate the effectiveness of this machine learning model as a comprehensive solution for predicting the life cycle impacts of both inorganic and organic chemicals. Nevertheless, this model offers potential in improving our understanding of the environmental impact of chemicals and contributes to the effort of ensuring a sustainable future.

Data-centric discussion on machine learning applications to LCA

Sunday, 2nd July - 17:15: Special Session: Applications of Machine Learning and Data Science in Industrial Ecology (A0.51 KOG)

Bu Zhao [1], ***Ming Xu*** [2], ***Qingshi Tu*** [3]

1. *University of Michigan,* ***2.*** *Tsinghua University,* ***3.*** *The University of British Columbia*

Machine learning (ML) has been increasingly applied to enhancing the life cycle assessment, in particular, by providing new methods to bridge the data gaps that compromise the accuracy of life cycle inventory (LCI) modeling. Despite initial successes, the performances of the existing ML-based methods are generally unstable and susceptible to a variety of factors. In this study, we aim to leverage some "failure experiences" (i.e., the challenges we observed either from our own work or literature review) to formulate a data-centric discussion on how to improve the ML applications in LCI modeling, with a focus on the following aspects:

1. Imbalanced data used for method development. A majority of ML methods for selecting proxies or creating new inventory data are derived from distance-based similarity algorithms. These methods are sensitive to the number of unit processes in the database and the varying magnitudes of the data (e.g., in ecoinvent, the values in the unit process data sets can range from 1.83×10^{-21} to 1.48×10^{8}). A common way to reduce this variation is through normalization/standardization of the original data. However, applying normalization/standardization to the LCI data remains a challenge, given the difficulty in achieving functional equivalence among all product systems in the database. Accordingly, the performance of existing similarity-based methods may only be satisfactory for certain scenarios (e.g., only the missing flows that are expected to have large values can be accurately predicted, and the prediction for those values less than 10^{-7} can be extremely unreliable). Similarly, there is usually a significant imbalanced representation of different industrial sectors in the databases as well. This imbalance in data availability may lead to low performance in predicting the missing flows for the unit processes belonging to those "underrepresented" industries.

1. Information for encoding the training data. Existing methods tend to use single/few sources of information from a given database for encoding (e.g., the flow values to encode a unit process). It may be feasible to improve the similarity evaluation using other information to formulate a multi-dimension encoding procedure (such as ISIC4 Group, word embedding of the description of a unit process).
2. Difference in the performance of a given ML method. The flow data of a foreground inventory model can be divided into "input" (e.g., electricity flow for a chemical synthesis process) and "output" (e.g., direct emissions of CO_2 from the process) sections. In many cases, obtaining the missing flow data in the input section is more important, as those flow data (e.g., electricity flow) are typically linked to the background technosphere datasets through their providers (e.g., a specific electricity production technology), which completes the entire life cycle model. In contrast, those in the output section can be relatively easier to estimate (e.g., elementary flows to the biosphere that may be estimated using empirical equations based on input flows). Therefore, it is important to investigate the difference in the prediction performance of a method, if any, between the input and output sections. If such a difference exists, given that we usually only have a relatively small database to train ML models, it may be beneficial to focus on improving the prediction of the missing flows in the input section. For example, the complete flow information from the output session can be leveraged as supplementary information to boost the prediction.

Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1)

Cost of a linear plastic economy: A case study of Indonesia

Sunday, 2nd July - 16:30: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1) (C1.31 KOG)

Satabdi Datta [1]***, Shreya Some*** [1]***, Jeeten Kumar*** [2]***, Joyashree Roy*** [3]

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Increased generation of plastic waste through production and consumption choices is a phenomenon across the world including the countries in the global south. Unmanaged plastic waste in the environment, insufficient initiatives to reduce, reuse and recycle plastic waste and poor waste management system is imposing indirect costs on the economy. Indonesia faces flood related vulnerabilities due to plastic wastes ending up in rivers, open drainage channels disrupting flow of water and runoff. These are reducing productivity of engineered system, economic sector's contribution impacting national budgetary allocation on various heads of expenditure. Low lying areas, areas near riverbanks and coastal parts of the country are specifically more vulnerable to these hazards. The present study initially establishes the link between flooding and plastics in the environment in Indonesia and then develops an econometric model to answer the research question does the incidents of recurrent flooding is impacting the national economy's annual expenditure burden. Using panel data for various provinces of Indonesia the study estimates an econometric model to answer the research question. Preliminary findings show there is significant impact on national economy in terms of annual expenditure. This study goal is to assess the economic cost implications of the actions and inactions towards plastic waste management. The analysis is carried out based on literature review, secondary data from government sources and interviewing key stakeholders in the study sites.
Submitted for the special session on "Sustainable circular economy"

From material stocks to circular economy potential: integrating reusability assessment into built environment stock analysis

Sunday, 2nd July - 16:45: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1) (C1.31 KOG)

Charles Gillott **[1], *Danielle Densley Tingley*** **[1], *Maud Lanau*** **[2]**

1. *The University of Sheffield,* ***2.*** *Chalmers University of Technology*

Although motivated by the potential for urban mining and transition to a circular economy, existing built environment material stock analyses typically focus on characterisation of the mass and location of different materials (i.e. "how much of which materials are where?"), and only sometimes consider the form that this is in (i.e. "how many of which components are where?"). Despite being valuable in identifying quantities of materials available for secondary use, this neglects to consider the technical feasibility and likelihood (i.e. "how might different buildings, components and materials be reused?"), and thus fails to understand the circular economy potential of the existing building stock.

To facilitate this, and ultimately aid in transition to a circular economy in the built environment, this project develops a methodology to integrate architectural and engineering considerations into bottom-up material stock analysis. This sees assessment of the technical feasibility of reusing individual elements at the building, component or material level through application of criteria derived from the 'Regenerate' circular economy assessment tool and engineering/architectural experience. Integration of this within the 'Bottom-Up Data collection: Material inventory ' (BUD-MI) assessment framework enables the generation of a suite of intensity coefficients, detailing not only the raw quantities of different materials but also the proportion that may feasibly be reused at different levels of the waste hierarchy. The probability associated with each level of reuse (i.e. building, component or material) is also considered to begin to identify element-wise reuse pathways that are more or less likely."

Just Copper? – Can a Circular Economy Balance Environmental and Social Concerns in the Metal-Energy Nexus

Sunday, 2nd July - 17:00: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1) (C1.31 KOG)

Sina Leipold [1]

1. *Helmholtz Centre for Environmental Research*

The transition to renewable energy sources is crucial for achieving carbon neutrality. At the same time, renewable technologies like wind turbines and solar panels require a lot more metals such as copper. This leads to new environmental and social challenges. This study aims to assess the potential of circular economy approaches to balance environmental and social concerns in the metal-energy nexus of copper. We evaluate different circular economy approaches such as recycling, reduction and reuse, using social and environmental science methods. Our results provide guidelines and recommendations for decision-makers and practitioners from industry and civil society. The goal is to stimulate research, initiate political and practical developments, and facilitate a just transition to renewable energy.
This presentation is planned to be part of the special session “ASSESSING PROGRESS TOWARDS A SUSTAINABLE CIRCULAR ECONOMY ACROSS SCALES”

Circularity strategies for China's building sector: a scenario analysis

Sunday, 2nd July - 17:15: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1) (C1.31 KOG)

Alessio Mastrucci [1], ***Fei Guo*** [1], ***Bas van Ruijven*** [1]

1. International Institute for Applied Systems Analysis

The building stock in China is responsible for a massive amount of energy demand and greenhouse gas emissions due to its large population, continuous economic growth, and ongoing construction boom. In addition to emissions for direct energy use, e.g. due to space heating and cooling, buildings also drive significant indirect emissions for construction activities and use of energy intensive materials, such as steel and cement. Thus, a demand-side perspective is needed to explore sustainable pathways for the China's buildings sector, accounting for stock dynamics and combined energy and material implications.

In this study, we explore a set of scenarios for the China's building sector considering a range of circularity strategies to reduce the demand for energy and construction materials. Starting from a reference scenario consistent with the Shared Socioeconomic Pathway SSP2, we analyze the effect of different measures, including 1) limitation of the increase in per-capita floorspace, 2) building lifetime extension, 3) increase of the building renovating rate, and a combination of these three measures.

We use a modelling framework combining the integrated assessment model (IAM) MESSAGEix-GLOBIOM and two end-use models for buildings (MESSAGEix-Buildings) and industry (MESSAGEix-Materials). We initially run the sectoral bottom-up model "MESSAGEix-Buildings" to assess the impacts of different circularity measures on building stock dynamics and related building material and final energy demands. We then use the combined IAM framework to analyzed the impacts of the above measures on the entire energy supply system.

The results of this analysis show that, by implementing the three described circularity measures, the China's building stock could peak around 2030 instead of 2040, as shown in the comparison with the reference scenario without these measures. Using the combined end-use and IAM framework, we estimate that the three combined demand-side measures could reduce the final energy demand in buildings by 11% compared to the reference scenario in the period 2020-2100. The reduction in total primary energy and CO_2 emissions from the energy supply system would respectively 3% and 5% for the same period.

Implementation of the analyzed circularity measures would require regulatory and incentive policies, e.g. tighter building codes and regulations on building materials, stricter land use policies for buildings, subsidy programs for building renovation, and so on. The results of this study can be used to support policy decisions at national and regional level to reduce demands for energy and materials and contribute to achieving climate mitigation targets.

ASSESSING THE IMPACT OF CIRCULAR ECONOMY STRATEGIES ON CO2 EMISSIONS IN THE UK TRANSPORT SECTOR

Sunday, 2nd July - 17:30: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1) (C1.31 KOG)

Gabriel Carmona [1]***, Zeus Guevara*** [2]***, Kai Whiting*** [3]***, Jonathan Cullen*** [4]

1. *Aluminium Stewardship Institute,* ***2.*** *Tecnológico de Monterrey,* ***3.*** *Université catholique de Louvain,* ***4.*** *University of Cambridge*

The transport sector plays an important role in socioeconomic development, as it allows for the mass movement of people and goods. Motorised mobility relies on energy flows (fuels), material flows and material stock, the latter in the form of vehicles and infrastructure. The global transport sector is also responsible for 37% of energy-related CO2 emissions.

In this study, we applied a decomposition approach to identify and quantify the elements that have a direct or indirect impact on energy and material related CO2 emissions across UK transport (car, bus and rail) from 1960 to 2015. The principal objective was to assess the influence of eleven factors primarily associated with carbon emissions produced via passenger mobility. These include energy conversion, material stock turnover, and service delivery. The empirical study of CO2 emissions data revealed that the rapid increase of carbon emissions, since 1960, was primarily attributable to the rising prevalence of car use and higher service demand. However, energy efficiency has, to some extent, reduced CO2 emission growth, in relative terms.
A second objective was to quantify the extent of which circular economy strategies, such as “end-of-life recovery and recycling”, “product lifetime extension”, and “sustainable lifestyle transitions”, can mitigate absolute carbon emission growth in the UK’s transport sector. A significant reduction in emissions was observed when these strategies were combined, compared to the 1960 baseline. Lastly, we discuss which low carbon policies, in addition to circular economy strategies, would need to be implemented on both the production and consumption sides of the UK economy, in order to achieve the national targets as set out by the Paris Agreement.

Determining the Average Sustainable Performance of German and Danish Urban Resource Centres

Sunday, 2nd July - 17:45: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 1) (C1.31 KOG)

Vitor Souza [1], ***Magnus Fröhling*** [1], ***Pedro Lopes Cardoso de Mattos*** [2], ***Perla Calil Pongeluppe Wadhy Rebehy*** [2], ***Daniela Pigosso*** [3]

1. Technical University of Munich, 2. University of São Paulo, 3. Technical University of Denmark

Urban Resource Centres (URCs) are multifunctional, purpose-driven organisations facilitating Preparation for Reuse (PfR) activities; namely reuse, repair, repurpose, remanufacturing, refurbishing and recycling. Often structured as social enterprises, URCs are key players to increase the circularity of resources, generating environmental and social benefits. The magnitude of their contribution has been seldom reported, however, and only for a few examples of URC. Developing theory around the URCs can support closing the resource circularity gap, which is currently beyond 90% worldwide - i.e. only 7.2% of resources are circular.

In previous research, five archetypes of URCs have been proposed, named after their core PfR activity: Sorting Centres - collection points featuring e.g. a second-hand shop -, Reuse Shops, Repair Cafes, Preparation for Reuse Parks - like circular shopping centres incubating smaller PfR businesses - and Shared Ownership Projects - without a physical centre, but promoting joint projects with schools or prisons. This research aims to define the Sustainable Performance of these URCs in the environmental, social and economic dimensions, and to quantify it for the five archetypes. Sustainable performance is defined based in literature and from a workshop organised with specialists. From this workshop, a questionnaire is also developed and a survey performed to collect data from URCs across Germany and Denmark, the two countries partnering this project.

Statistical Analysis of the results are performed, and performances for each archetype are inferred. The Sustainable Performance of an URC is defined by the recovery rate, the number of visitors/costumers, the number of vulnerable people employed or engaged, the fraction of the expenses covered through public funding, and the avoided environmental impact - prevented minus generated. Partial results are available for the archetype of the Sorting Centre. Reuse rates range from 0.235 for books, up to 1.000 for building products made of wood, while achieving 0.725 for furniture and 0.844 for electronics. The number of visitors are estimated at 750 per month, while helping around 500 vulnerable people finding a job and providing training for more than 2000 unemployed people per year. At least half of their expenses is funded by public money through e.g. waste fees. Finally, for textiles, sorting centres can reduce CO_2 emissions by 15kg per kilogram of textile waste prevented. If one kilogram of textile is reused, the reduction is of 8kg of CO_2 avoided emissions; if it is recycled, the reduction is of up to 3kg.

Urban Resource Centres have a pivotal role in closing the resource circularity gap. Defining and determining their sustainable performance provides guidance for public policies in prioritizing funding for such organisations, and to support further modelling the evolution of resource circularity in urban areas. Quantification of performances can be further generalised and analysed using examples from another countries; in this research, only URCs from Germany and Denmark were surveyed.

*** This article belongs to a special session about "Circular Economy potentials/limits/trade-offs concerning all sustainability dimensions" (Prof. Wiedenhofer)**

Special Session: Assisting a Circularity Transition in the Timber Construction and Wood Sectors

A systematic analysis for the wood value chain in Norway to define the potential and challenges of end- of-life management

Sunday, 2nd July - 16:30: Special Session: Assisting a Circularity Transition in the Timber Construction and Wood Sectors (A1.44 KOG)

Roja Modaresi [1]***, Lone Ross*** [2]***, Daniel B. Müller*** [3]***, Lizhen Huang*** [3]***, Erik Trømborg*** [4]***, Hanne K. Sjølie*** [5]

1. *(NTI) Norwegian Institute of Wood Technology,* ***2.*** *Norwegian Institute of Bioeconomy Research,* ***3.*** *Norwegian University of Science and Technology,* ***4.*** *Norwegian University of Life Sciences,* ***5.*** *Inland Norway University of Applied Sciences*

Belongs to the special session:

- Assisting a circularity transition in the timber construction and wood sectors

To enable and support a transition to a sustainable, competitive and technologically optimized circular wood value chain, it is essential to determine the environmental, economic, socio-economic and societal impacts by using a trans-disciplinary approach. The circWOOD project will provide this support by tracking materials flows and determining environmental, social and economic impacts and opportunities associated with different technological options and under different scenarios.

Understanding the consumer market's readiness to adopt the innovation of circular construction materials is crucial for unlocking reclaimed wood's potentials in the construction sector. A recent survey of ~1000 end-users' attitudes, acceptance and willingness-to-pay for residing in buildings made from reclaimed wood will be presented. The survey represents the main residency market segments in Norway and will identify subgroups that are more and less willing to adapt new technologies.

In different tasks of the project, regional sustainability assessment will be performed to account for forest sector impacts such as changes in harvest, transport and industrial production by an improvement in the wood cascading options as identified in NFSM (The Nordic Forest Sector Model), which is a partial equilibrium model with a high regional resolution. In addition, a dynamic MFA model with building sector in focus will be developed to simulate the wood flows associated with the building stock (wood demand due to construction and renovation) and the supply of reclaimed wood from construction, renovation, and demolition. Expansion of the system to include construction and end-of-life management by including waste stream from all the relevant sectors, will enable the testing of alternative strategies for reuse and recycling. Technological possibilities for reuse and recycling are identified and included in the scenarios. The diversity and possibilities of the new products from reclaimed wood can be increased by keeping the material in the upper part of the waste hierarchy framework, where reuse, repair, refurbish, and remanufacture without changing functionality are prior to repurpose and recycling, and energy recovery.

As a result, the upstream forest model will be integrated with the dMFA model for building and including end-of- life models and scenarios to create a full MFA in the entire value chain. The model will be combined with emission factors to assess environmental impacts of cascading in different scenarios. Suggestions for calculation of the carbon sequestration potential for different scenarios by considering the number of occurrences of wood products that stay in the circle for reuse and recycling will be presented.

Mapping qualities and quantities of waste wood in Norway

Sunday, 2nd July - 16:45: Special Session: Assisting a Circularity Transition in the Timber Construction and Wood Sectors (A1.44 KOG)

Kristina Bringedal Gedde [1], ***Daniel Müller*** [2], ***Andreas Stenstad*** [3], ***Erik Larnøy*** [1], ***Lone Ross*** [1]

1. Norwegian Institute of Bioeconomy Research, 2. Norwegian Univ. of Science and Technology, 3. NTI (Norwegian Institute of Wood Technology)

This abstract belongs to the proposed special session on the circularity transition in the timber-built environment, organized by Wendy Wuyts and Roja Modarasi.

Wood from sustainably managed forests is a renewable resource with several applications. Wood-based products can be used as a substitution for more emission-intensive materials. The substitution effect and the biogenic carbon in trees make wood a resource for wider application and market uptake in emission-intense sectors. Given current global market demands for wood exceeding the supply of sustainably managed forests, reusing or recycling a higher degree of secondary wood is a rational strategy. In Norway, wood waste is one of the largest waste fractions, and in 2020, 82 % of the generated waste wood was incinerated after only 1 use-cycle[1]. To effectively utilize the secondary resource and identify the possible reuse and recycling applications in end-use products, it is essential to develop an understanding of the composition and volumes of the wood waste fractions.

In this study, fraction analysis at multiple recycling stations in Norway has been carried out. Data about the source of the wood waste, types of fractions, and quality (stiffness, strength) have been collected. The study shows that the two largest fractions of wood waste are untreated solid wood (30.9 %) and wood packaging (27.5 %). The waste from the construction industry contained a larger share of untreated solid wood, while the household waste was more varied. A large fraction of the household waste consisted of wood-based panels.

The different waste wood fractions are reusable and recyclable to different degrees. Höglmeier (2017) defines load-bearing wood structures as a waste fraction with a high reusability potential.[2] In this study 60 percent of the untreated solid wood (and 18.5 percent in total) was classified as structural wood. Höglmeier further defines untreated solid wood as recyclable for producing particle board or OSB (oriented strain board) panels. This also holds true for wood packaging. Wood-based panels or treated solid wood on the other hand are more difficult to utilize in secondary cascading. In total, the current potential for reuse or recycling of the wood waste collected by recycling stations is close to 60 percent.

To estimate potential quantity of waste wood fractions in future years, a dynamic material flow analysis (MFA) model will be developed. MFA is a tool developed by Baccini and Brunner (1991) to follow materials through flows, stocks, and processes in a mass-balanced and well-defined system[3]. A dynamic MFA model accounts for the inertia in the built environment, which will influence future secondary resources. The model will include a building stock model based on Müller's (2006) building stock model [4]. Building types, cohorts, and material intensities will be defined and act as a basis. The model will be validated with data from the conducted FAs.

[1] "Bygg- og anleggsavfall - Avfall fra nybygging, rehabilitering og riving : resultater og metoder," ssb.no, accessed August 26, 2022, https://www.ssb.no/natur-og-miljo/artikler-og-publikasjoner/bygg-og-anleggsavfall.

[2] Karin Höglmeier, Gabriele Weber-Blaschke, and Klaus Richter, "Potentials for Cascading of Recovered Wood from Building Deconstruction—A Case Study for South-East Germany," *Resources, Conservation and Recycling* 117 (February 1, 2017): 304–14, https://doi.org/10.1016/j.resconrec.2015.10.030.

[3] *Metabolism of the Anthroposphere* (Berlin: Springer, 1991).

[4] Daniel B. Müller, "Stock Dynamics for Forecasting Material Flows—Case Study for Housing in The Netherlands," *Ecological Economics* 59, no. 1 (August 5, 2006): 142–56, https://doi.org/10.1016/j.ecolecon.2005.09.025.

A novel data acquisition method for existing building information modelling

Sunday, 2nd July - 17:00: Special Session: Assisting a Circularity Transition in the Timber Construction and Wood Sectors (A1.44 KOG)

Georgios Triantafyllidis [1], ***Lizhen Huang*** [1]

1. *Norwegian University of Science and Technology*

Developing strategies that are aiming towards the maximization- and of a more reasonable way of reusing existing materials and building elements from the existing building stocks, can have significant impact towards the reduction of waste generation, CO2 emissions, and extraction of novel resources, among others. To do so, there is a need to assess the existing building stock (quantitative and qualitative), as well as its temporal availability and its reuse potential, among others. Building Information Modeling (BIM) can serve as a depository of the information that needs to be analyzed, and therefore supports the assessment of the existing building stocks. In addition, BIM facilitates the exchange of the centrally stored information among different actors, which supports communication, collaboration, and decision-making. However, BIM models for existing buildings are limited and are mostly available for newer constructions. In addition, creation of BIM models for existing buildings with advanced data capturing methods such as 3D scanning stays a costly and time intensive operation, while at the same time it does not include information about the materiality, quantity, and quality of the building-materials and elements. Here we propose a new method for the creation of BIM models for existing buildings. We exploit the information existed in the Norwegian building registry to generate BIM models by including the geometrical and non-geometrical information from the database. Using existing information from the database, together with domain knowledge about building design and construction, we develop a method for creation of BIM models for existing buildings. We consider and populate the models with information that is relevant for enabling the reuse of existing building stocks. Finally, the goal is to test in future research whether, and to what extent we can apply the proposed method at the city level, to understand implications of building stocks' reuse on a bigger scale. The reuse of existing building stocks can support the reduction of environmental risks. The proposed method offers a simple alternative for creation of BIM models for existing buildings, by transforming tabular data, and by including domain knowledge, into 3D models that contain qualitative and quantitative information, as well as temporal and georeferenced information of existing stocks.

The impacts of combined forest management and wooden construction on carbon fixation in Japan

Sunday, 2nd July - 17:15: Special Session: Assisting a Circularity Transition in the Timber Construction and Wood Sectors (A1.44 KOG)

Naho Yamashita **[1]*, Tomer Fishman* [2]*, Chihiro Kayo* [3]*, Yuki Hiruta* [1]*, Hiroaki Shirakawa* [1]*, Hiroki Tanikawa* [1]**

1. Nagoya University, 2. CML Leiden, 3. Tokyo University of Agriculture and Technology

Forests can play an important role in realizing a carbon-neutral society as large carbon stocks. Trees absorb and fix carbon as they grow, and once matured they may be processed into various products such as wooden houses, furniture, and paper that maintain carbon out of the atmosphere. Timber used for buildings remain in society for a long period of time, and can therefore be considered as carbon stocks in cities. There have been some estimations of the amount of carbon stock in Japan, but previous studies focused on either natural carbon stocks in forests or on anthropogenic carbon stocks in the city. The total amount of carbon stock fixed in both nature and cities has not been discussed in a comprehensive way.

This study introduces an interlinked material flow analysis (MFA) model in which the timber demand for wooden houses in cities is connected with the timber supply from the forest, to estimate the current natural and anthropogenic carbon stock and its potential futures in Japan. We compare multiple scenarios of future demand for houses estimated by population change, with varying combinations of house types (detached houses and apartments), structures (wooden and non-wooden), and lifespans. A stock-driven MFA model estimates the total inflows, outflows, and stocks of timber and carbon in city buildings. Then, to meet the demand for timber, an interlinked model estimates the trees that are logged from the forest, calculates the required reforestation, and the age composition in forests are changed accordingly while taking into account tree species and their carbon stocks. Finally, based on the amount of timber stocked in city buildings and grown in forests, the total amount of carbon stock is estimated and compared among scenarios. Logging and reforestation are repeated every 5 years for the estimation period from 2017 to 2100.

Carbon stocks reach the largest amount of 1.0 billion t-C in 2100 in a scenario in which people prefer detached houses and wooden structures. This is 15.1 million t-C higher than a BAU scenario that extends current trends. On the other hand, a scenario with less detached houses and the constant wooden housing rate shows the smallest amount of total carbon stock throughout the estimation period. In all scenarios, total amount of carbon stock is expected to increase from 2017 to 2045, however, the year-to-year rate of total carbon stock will decline after 2050, which means the effect of increasing carbon stock is diminished. This may occur because of a decline in the carbon absorption rates of forests: in this estimation, the percentage of tree age compositions over 61 years of age or older reach over 95% by 2100 and the carbon stock in forests become saturated.

The findings implicate that the domestic demand for timber for wooden houses in Japan seems insufficient to stop the aging of forests and this can also be a negative from the perspective of carbon neutrality. Beyond policies to promote timber use for wooden houses, Japan needs to consider ways of expanding the timber use for other long-lasting commodities such as non-residential buildings, infrastructures, or furniture.

Material flow analysis of wood in the UK from roundwood deliveries to finished product applications.

Sunday, 2nd July - 17:30: Special Session: Assisting a Circularity Transition in the Timber Construction and Wood Sectors (A1.44 KOG)

Rebeka Anspach [1]***, Michal Drewniok*** [2]***, Matt Roberts*** [3]***, Stephen Allen*** [1]***, Rick Lupton*** [1]

***1.** University of Bath,* ***2.** University of Leeds,* ***3.** University of California, Berkeley*

At the midst of growing efforts to decarbonise and replace high-carbon engineering materials with low-carbon alternatives, the demand for global industrial roundwood is predicted to quadruple by 2050 (World Bank, 2016) and go beyond the capacity of sustainable supply. In this context, it is essential that we plan for the future use of our wood resources and understand wood flows on a country-level. This article presents the first comprehensive breakdown of the UK's wood supply chain from a territorial perspective revealing the magnitude of flows occurring in 2019 in primary wood transformation industries all the way to finished product applications. We then assess opportunities to free up high-value wood by lightweighting and by the use of engineered wood alternatives for different finished product applications.

The largest consumers of forest products in the UK are the energy sector consuming 9 Mt of wood pellets, followed by the packaging industry (3.8 Mt) and the furniture industry (3.6 Mt). This study reveals that even though half of the sawn wood (2.5 Mt) consumed in the UK enters the construction industry, only 10% of sawn products are used for the structure of new residential houses while the rest is being utilised for refurbishment, joinery, and repair works. The result of this analysis shows whether strategies to substitute high-value wood in products by engineered wood alternatives and different levels of product lightweighting would free up enough high-value wood, allowing an increase in timber construction without increasing imports.

World Bank, 2016. *Forest Action Plan.* Washington: W.B. Group.

Special Session: Biodiversity Loss and Impact Indicators in LCA

Global freshwater eutrophication: regionalized characterization factors for phosphorus and nitrogen impacts on fish biodiversity

Sunday, 2nd July - 16:30: Special Session: Biodiversity Loss and Impact Indicators in LCA (B0.17 KOG)

Jinhui Zhou [1]***, José Mogollón*** [2]***, Peter van Bodegom*** [1]***, Arthur Beusen*** [3]***, L. Scherer*** [2]

1. *Institute of Environmental Sciences (CML) - Universiteit Leiden,* ***2.*** *Leiden University, CML,* ***3.*** *Department of Earth Sciences - Utrecht University*

Excessive use of phosphorus (P) and nitrogen (N) in agriculture, industry, and household causes eutrophication and toxicity in freshwater across the world. To better understand nutrient-induced impacts on freshwater ecosystems, improved life cycle impact assessment (LCIA) models for distinct parts of the cause-effect chain are required at a high spatial resolution. The fate and effect of nutrients were analyzed separately through the development of fate (FFs) and effect factors (EFs). Half-degree-gridded FFs were estimated utilizing the IMAGE-Global Nutrient Model (GNM). EFs were developed based on establishing species sensitivity distributions of freshwater fish against nutrient concentrations for hundreds of ecoregions over the world. Eventually, FFs and EFs were combined into regionalized characterization factors (CFs) for freshwater eutrophication for direct and diffuse emissions of P and N, as well as excessive erosion due to land use at a half-degree resolution. The CFs further considered global extinction probabilities to scale regional to global species loss and nutrient limitation. Results showed that the CFs for P and N impacts on freshwater fish are higher in densely populated regions that encompass large lakes and the headwater of large rivers. This study highlights the relevance of considering freshwater eutrophication impacts through both P and N emissions and identifying the limiting nutrient for impact assessment.

Biomass to Biodiversity: representing endpoint fishing impacts on marine ecosystems in LCIA

Sunday, 2nd July - 16:48: Special Session: Biodiversity Loss and Impact Indicators in LCA (B0.17 KOG)

Chloe Stanford-Clark [1]***, L. Scherer*** [2]***, Francesca Verones*** [3]***, Arnaud Hélias*** [1]

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Introduction

Despite increasing awareness of the multitude of synergistic threats affecting the marine environment, marine biodiversity impact coverage is still scarce in the current Life Cycle Impact Assessment (LCIA) framework. This is even more true for over-exploitation, a well-established driving force of marine biodiversity loss (IPBES 2019), which is out of the scope of current LCA. This work supports the development of the recently proposed fisheries pathway, quantifying biodiversity loss resulting from biomass removal by marine wild capture fisheries. The resultant depletion of individual, exploited stocks (a species in a region) is taken as an initial proxy of ecosystem damage, and is being discussed as a novel impact pathway deliverable for Phase 3 of the Lifecycle Initiative project GLAM.

Materials & methods

Individual stock Characterisation factors (CFs), regionalised by FAO Major Fishing Area, are computed from elements derived by the Schaefer population model and CMSY+ algorithm (Froese et al. 2017), following the approach proposed by Hélias et al. (2023). Combining fate and effect factors, CFs encompass the current catch and biomass, the resilience of the species and the carrying capacity of the habitat. Input fishing pressure data is a 3-year average of the 2018 FAO global catch time series. An estimation of the additional, unreported biomass removed as discarded by-catch is also included, using a biomass-weighted approach based on regional FAO discard rates (Pérez Roda et al. 2019). Various potential methods of deriving the Ecosystem Quality endpoint metric (PDF) are investigated to explore how marine biodiversity loss could be represented in LCIA.

Results & Discussion

Operational endpoint CFs are computed for fish stocks using a biomass-based approach compatible with fisheries management tools and GLAM, summarised below in Figure 1. Several sets of CFs are available to enable the most appropriate assessment possible with the information available in the inventory.

The endpoint metric PDF is typically derived from a change in species richness but fisheries data is reported in biomass, making species abundance information highly relevant to include in the endpoint indicator. This is the approach used in Fig 1, but several possible approaches to combine stock assessment and/or ecological biodiversity indicators with this LCA endpoint metric are possible and are currently under investigation, based on species richness, abundance, fisheries management parameter or ecological index.

Conclusions

Marine fisheries cause a myriad of complex and inter-linking environmental damages. This work reflectsthe first operational step in the inclusion of this significant ocean-based impact in LCIA. This more comprehensive quantification of fisheries impacts can be used as a tool to better inform marine biotic resource use, from more sustainable fisheries management choices to environmental labelling. The addition of discards is an important progression in the impact pathway. The next step will extend the assessment to a more holistic ecosystem perspective of biodiversity loss. The approach currently under development, based on dynamic ecosystem model Ecopath-with-Ecosim (Christensen and Walters 2004), should provide more holistic quantification by also taking into account the dynamic trophic interactions influenced by the removal of biomass during fishing activity.

Non-native species impacts on biodiversity in the framework of Life Cycle Assessment

Sunday, 2nd July - 17:04: Special Session: Biodiversity Loss and Impact Indicators in LCA (B0.17 KOG)

Philip Gjedde [1], ***Jan Borgelt*** [2], ***Francesca Verones*** [3]

1. NTNU, Department of Energy and Process Engineering, 2. Norwegian University of Science and Technology, 3. NTNU

The global transportation of traded commodities facilitates the relocation of non-native species. Once non-native species become introduced into new environments, they can establish, become invasive and consequentially threaten the balance of the invaded ecosystem. Life Cycle Assessment helps to assess environmental impacts across value chains. However, within this framework, the ecological impacts of non-native species introductions are not yet accountable due to a lack of methodology. We developed regionalized characterization factors (CFs), expressed as the potentially disappeared fraction (PDF) of native species due to exotic species introductions per unit of goods transported between two locations. Our CFs focus on terrestrial or marine species in two separate sets of CFs. By combining global data on species occurrences of non-native species and native species distribution maps and their conservation status to trade quantities and patterns, we generated CFs representing terrestrial impacts for 36,975 combinations of trading partners, and marine impacts of routes between all greater ports. The findings suggest that risk and ecological consequences of introduced non-native species greatly varies per trading partner and route. Furthermore, the trade-mediated relocation of non-native species can be, in some cases, as damaging as climate change effects of transporting commodities.

Addressing marine biodiversity loss with expanded impact assessment models

Sunday, 2nd July - 17:20: Special Session: Biodiversity Loss and Impact Indicators in LCA (B0.17 KOG)

Jennifer Anderson [1], ***Sedona Anderson*** [2]

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Biodiversity loss is occurring at the fastest rate seen in millennia, and research suggests we are experiencing a 6th mass extinction. While demand for public discourse and policy addressing climate change has grown in recent decades, a lack of knowledge and action persists when it comes to addressing biodiversity loss. BAMBOO is a Horizon Europe project that aims to provide an updated methodology for measuring biodiversity impacts from international biomass trade for use in life cycle assessment (LCA) and multiregional input-output analysis (MRIO), as well as a publicly accessible tool for identifying leverage points to halt and reverse biodiversity loss. While considerable progress has been made in advancing the impact assessment methodology, there are still critical knowledge gaps requiring more research. A notable imbalance exists between terrestrial and marine impact categories, with the latter being underrepresented. Historically, marine ecosystems have also been protected at a much lower rate than their terrestrial counterparts. Developing and expanding marine impact categories is critical for adequately protecting marine biodiversity. Additionally, using multiple endpoint indicators is important for a comprehensive view of biodiversity impacts. Current research often focuses on species richness, which alone may not provide a holistic understanding of impacts. BAMBOO aims to explore both new impact categories and new biodiversity metrics.

Species richness is a valuable and well-understood indicator to be included as one of multiple indicators in a comprehensive impact analysis. In BAMBOO, we develop new marine impact indicators, among others, for ocean acidification. We build on current models for ocean acidification to create spatially explicit characterization factors that improve on the precision of previous results. This effort will increase the representation of marine impacts, as well as improve impact accuracy using the species richness indicator.

In addition to species richness, BAMBOO utilizes functional diversity as an endpoint indicator. This allows us to assess not only species count data but also functionally significant species trait data. BAMBOO is applying functional diversity methodologies used in freshwater ecosystems to assess climate change impacts on marine species. In the freshwater realm, research shows some locations worldwide might face complete loss of freshwater fish functional diversity due to climate change. In extending this methodology to marine ecosystems, we will simulate how geographical ranges of marine species change under various future climate scenarios and strengthen our understanding of marine biodiversity impacts.

Advancements in impact assessment methodologies have improved our understanding of current and potential future biodiversity loss. These assessments, however, are often applied to terrestrial ecosystems using limited endpoint indicators. As part of BAMBOO, we are working to expand current marine impact categories and endpoint indicator inclusion to reduce and reverse biodiversity loss associated with global trade.

Modelling impacts of land use on functional diversity in Europe

Sunday, 2nd July - 17:36: Special Session: Biodiversity Loss and Impact Indicators in LCA (B0.17 KOG)

***Francesca Rosa* [1], *L. Scherer* [2], *Stephan Pfister* [3], *Peter van Bodegom* [4], *Stefanie Hellweg* [3]**

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Land use is one of the main drivers of biodiversity loss across the planet, and it is connected to people's final consumption through global supply chains. Consequently, it has become imperative to quantify the impacts of land use at large spatial scales to properly assess consumption biodiversity impacts. While biodiversity is very complex and multidimensional, most of the currently available models and assessments have focused on quantifying the number of species lost or the loss in species abundance. However, these indicators neglect the specific ecological importance of species in a community and species' contributions to ecosystem functions. To cover this gap, we assessed the impacts of land use on plant functional diversity at the European level, differentiating various land use classes and European bioregions. We combined a database of vegetation plots containing the occurrence of species (sPlot and European Vegetation Archive) and their traits (TRY) with several spatial data sources on land use and potential natural vegetation. To calculate land use impacts, we considered three functional diversity metrics representing three different aspects: functional richness, evenness, and divergence. Our results show that the presence of human-modified land compared to natural vegetation caused a decrease in functional richness, an increase in functional evenness, and a decrease in functional divergence for most land use classes and most bioregions. The effect on functional richness was much stronger than for the other two metrics. Our findings suggest that land use can significantly alter the functional diversity of ecosystems, especially functional richness, and thus reduce ecosystem resilience. A better understanding of how this is related to the effect on species richness should be investigated in future research.

MFA case studies 1

Urban Scale Evaluation of Building Integrated PV Waste: A Dynamic Material Flow Analysis

Sunday, 2nd July - 16:30: MFA case studies 1 (B0.25 KOG)

Julius Jandl [1] ***, Helmut Rechberger*** [1] ***, Bettina Mihalyi-Schneider*** [1] ***, Abraham Yezioro*** [2] ***, Sabrina Spatari*** [2]

1. Vienna University of Technology, 2. Technion

With the densification of urban areas in Mediterranean climates and the need to mitigate climate change, cities are looking to use building integrated photovoltaic (BIPV) systems to harvest renewable energy and potentially produce decentralized power. Rapid urban development in Israel is expanding the urban residential building stock in the form of high-rise buildings. These buildings offer promising space to scale BIPV installations, which would enable them to shift from being energy consumers to energy producers (1). Yet, PV technology comes with its own obstacles: the need to establish an infrastructure for dismantling PV panels from buildings and technology to enable recycling those materials.

Today, due to low waste volume most waste PV panels are landfilled (2); thus, a circular approach is needed to allow a reuse of PV materials. To recycle PV panels, the individual layers of solar cell, polymer and back-sheet need to be separated either by mechanical, thermal or chemical processes, which requires investment in technology development (3). Our objective is to evaluate the emerging waste streams from urban scale BIPV installations and their associated environmental impact caused by the recycling process at end-of-life (EOL). Several case studies on emerging PV waste ((4), (5)) have assessed utility scale installations at national levels. Here, we evaluate prototype neighbourhoods equipped with BIPV systems using architectural design software. As a first step, we developed a stock-driven dynamic material flow analysis model (DMFA) in Python. We used the Rhinoceros 3D modeling software, its Grasshopper visual programming plugin and the Ladybug Tools plugin to quantify neighbourhood scale BIPV materials in the Tel Aviv area. Several building typologies were combined with real irradiation data to create the simulated neighbourhoods. These simulations provide the available area in the prototypical neighbourhood than can be used for BIPV. These data serve as basis for the DMFA. Using a Weibull lifetime distribution and a total building lifespan of 100 years, the emerging waste for each year is calculated by age-cohorts. It is assumed that panels that reach their end of life, are replaced. The model also provides the energy that can be harvested per year according to the orientation and shape of the buildings in the neighbourhood block. First results were achieved for different building typologies using crystalline Si (c-Si) PV technology on roofs and thin-film technology on facades. The waste streams lie on a scale of several thousand tons of PV waste after the considered lifespan of 100 years while the generated energy reaches values of between 6.6 to 10.7 GWh/year, which far exceeds the demand from the buildings, necessitating storage provision. The quantities of PV waste clearly show that a sophisticated waste management system will be necessary.

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Modelling the transition towards a low-carbon global aluminium cycle with technology-explicit material flow analysis

Sunday, 2nd July - 16:45: MFA case studies 1 (B0.25 KOG)

Moritz Langhorst [1], ***Romain Guillaume Billy*** [1], ***Christian Schwotzer*** [2], ***Felix Kaiser*** [2], ***Daniel B. Müller*** [3]

1. Norwegian Univ. of Science and Technology, 2. RWTH Aachen University, Department for Industrial Furnaces and Heat Engineering, 3. Norwegian University of Science and Technology

Aluminium is a key enabler for the transitions in energy and transport. At the same time, GHG emissions from aluminium production can be hard to abate. To meet climate targets in the face of increasing aluminium demand, it is urgent to develop and deploy low carbon production technologies, such as inert anodes and electrically or hydrogen-heated melting furnaces. However, the large investments and long lifetimes associated with industrial assets can slow down the transition, and thus limit the emission reduction potential of these emerging technologies.

While future scenarios for the aluminium cycle and its associated emissions have already been developed in previous studies, there has been less focus on the dynamics of industrial assets or technology stocks and their influence on GHG emissions. Here, we use stock-lifetime-driven material flow analysis to model the evolution of global primary (smelters) and secondary (melting furnaces) aluminium production capacities. We thus expand existing models of the aluminium cycle by adding a technology layer to explicitly consider the inertia of technology stocks. We use this new model to quantify the influence of parameters specific to the technology layer, such as market penetration and retrofitting rate of emerging technologies, as well as parameters influencing the global aluminium cycle, such as population, aluminium stock per capita, scrap usability, electricity-mixes, end-of-life collection rates and various fabrication yields. We also conduct a scenario analysis for future GHG emissions from the global aluminium cycle.

In a business-as-usual scenario, total GHG emissions related to the smelters and melting furnaces would rise from 710 Mt CO_2-eq./yr in 2020 to 920 - 1400 Mt CO_2-eq./yr in 2050 depending on the aluminium stock per capita. Our results show that around 14 - 18 % of the annual GHG emissions in 2050 could be avoided by implementing inert anodes and replacing fossil fuel by hydrogen or electricity in melting furnaces. This would require deploying those emerging technologies in new plants as soon and as fast as possible. Existing plants would need to be either retrofitted with new technologies and/or progressively phased out earlier than expected. However, a limitation of cumulative emissions compatible with a 2 °C scenario can only be achieved under three conditions: 1) aluminium stocks per capita must stay within the reference demand scenario, 2) collection and recycling systems need to be improved to be able to absorb all the available post-consumer scrap, and 3) aluminium electrolysis must switch to low carbon electricity sources as fast as possible.

Bridging climate and circular economy related policy targets: Insights from material requirements in the Swedish renewable electricity system

Sunday, 2nd July - 17:00: MFA case studies 1 (B0.25 KOG)

Georgia Savvidou [1], *Filip Johnsson* [1]
1. Chalmers University of Technology

Despite the potential role of low-energy-demand scenarios or degrowth, the expansion of clean energy technologies, including wind power, will need to continue to address both decarbonization of the existing electricity system and the electrification of the transport and industry sectors. Although several studies have been conducted on the global material requirements for transitioning to a low-carbon electricity system, research at the national level is still insufficient. Additionally, the possibility of the electricity system serving as a source of secondary materials has yet to be fully explored. We address these gaps, by applying a dynamic material flow (MFA) to policy-relevant scenarios in order to analyze the stocks and flows in the wind turbine infrastructure toward 2050 in Sweden. We evaluate the demand for bulk materials (concrete, steel) and critical materials (including rare earth elements).
We demonstrate that the investigated scenarios with their increasing share of wind energy lead to a substantial increase in the stocks and flows of both bulk and critical materials. Previous studies argue that the high demand for primary materials may be limited to the energy transition period. In that regard, Sweden presents an interesting case because it has committed to reducing GHG emissions to net zero by 2045 but the energy scenarios we use run up to 2050. Indeed, we show that outflows of materials from decommissioned plants follow an increasing trend up to 2050, while inflows of materials in new installations follow a decreasing trend toward the end of the scenario period. This shows the beginning of a trend toward higher circularity potential which could be realized through for example recycling of materials outflows. The development of material stocks and flows in wind power is sensitive to changes in lifetimes. Longer lifetimes reduce the potential primary supply bottlenecks thereby showing a synergy between climate and recycling-related policy goals, but at the same, longer lifetimes lessen the potential for secondary supplies, showing a trade-off between climate and recycling policies. Material efficiency improvements can also substantially reduce the material demand for wind technologies.

For wind energy infrastructure to comply with emission targets, the production of materials such as steel and concrete will need to be decarbonized at a rate in line with climate targets. We show that should these sectors' emissions remain at current levels, the embodied emissions for wind infrastructure will exceed the operational emissions of electricity generation in Sweden. These materials thus deserve attention in strategies to mitigate climate change and sustainable resource use.

National policy needs to focus on emissions of the entire value chain including steel and concrete industries, maximizing the extraction of materials from urban mine, promoting the implementation of recycling processes, and enhancing material efficiency through technological advancements.

What is the extent and fate of Fossil Carbon accumulation in our Technosphere?

Sunday, 2nd July - 17:15: MFA case studies 1 (B0.25 KOG)

Kaan Hidiroglu [1]***, Stefano Merciai*** [2]***, Franco Ruzzenenti*** [1]***, Klaus Hubacek*** [3]

1. Integrated Research on Energy Environment and Society (IREES), Energy Sustainability Research Institute Groningen (ESRIG), University of Groningen, 2. 2.-0 LCA consultants, 3. University of Groningen

Fossil carbon is essential to maintain the human technosphere, most prominently for energy generation (energy use) and secondly as material inputs to industrial processes (non-energy use) to produce many different products, durable goods and infrastructure. These products can be categorized as durables and non-durables based on their lifetimes in their "use phase". Durables have a lifetime of more than a year, whereas the other less than a year. Emission and waste streams affiliated with energy and non-energy use of fossil carbon-based fuels have been studied extensively. However, the fate of fossil carbon contained in durables and non-durables is still unknown. This leads to the following questions: What is the amount of fossil carbon that stays in the human technosphere in comparison to annual fossil fuel emissions? When and how much of the fossil carbon content in these products is released as emissions to the atmosphere? When and how are these durables disposed to waste streams (most prominently landfills and then incinerators or littered) and how long do they reside in landfills before being released as emissions or leakage? Based on Material-Flow Analysis, we analyze Exiobase 3 Hybrid-Supply Use Table for 2011to observe the flow of fossil carbon in our technosphere. Our estimations show that most of the fossil carbon is throughout for our economic system and goes straight into the atmosphere, whereas the share of extracted fossil carbon that remains in the Technosphere is only about 5%. The highest amount of fossil carbon contained in durables is in heterogeneous machinery, followed by bitumen, rubber and plastics, and finally iron and steel. Based on these results, we extend our estimation of fossil carbon accumulation in durables to the period of 2004-2019, finding the contribution to fossil carbon accumulation as the same amount as global CO_2 emissions in 2021(37 Gt CO_2-eq.). Next we show that the 34% of the fossil carbon in durables between 2004-2019 will not complete their lifetime for the following 100- years. These products are still in use in the technosphere; hence are not sent to landfills as waste or released as emissions in incinerators yet. Overall, more than two-thirds of all fossil carbon in durables end up in landfills (69%), less than one-third in incinerators (28%) and the rest is littered waste. 90% of the fossil carbon that is sent to landfills need at least 50 years to decompose; hence acting as (temporary) fossil carbon sequestration. Finally, our study paves the way for future research aimed at reducing our dependency to fossil carbon resources for economic growth through reducing fossil carbon inflow and throughput.

Helium supply and demand: Material flow analysis of a noble gas

Sunday, 2nd July - 17:30: MFA case studies 1 (B0.25 KOG)

***Ankesh Siddhantakar* [1], *Komal Habib* [2], *Steven B Young* [3]**

***1.** School of Environment, Enterprise, and Development, University of Waterloo, **2.** University of Waterloo, **3.** Univeristy of Waterloo*

Helium (He) is listed as a critical raw material by the USA, EU, Canada, and other jurisdictions, yet it has been overlooked in the resource sustainability literature compared to metals and other extracted resources. This unique resource is attracting increasing attention in recent years due to its significant role in healthcare and advanced technologies. Helium is irreplaceable in many applications for its unique physical and chemical properties. It is stored and transported as cryogenic liquid, then distributed as liquid or as compressed gas.

We map global helium flows for 2019. Global flows and stocks of helium are tracked from extraction in the lithosphere as a coproduct of hydrocarbon natural gas to dispersion into the atmosphere after use. As a noble gas helium does not change its form or mix over its life cycle, providing a uniquely pure flow through the economy. We quantify stocks and flows with data from UN Comtrade, national geological data, and industry-specific sources. We considered growing international demand, supply patterns, and supply challenges.

Global supply is challenging and has experienced multiple shortages since 2006. Helium resource production is concentrated in the USA, Qatar, and Algeria. Approximately 27 kt of helium was refined in 2019. Helium is used as coolant for magnetic resonance imaging (MRI) machines in healthcare (approx. 30% of consumption), as a lifting gas, in research labs, and in advanced manufacturing. Results suggest that liquid helium product is susceptible to extraordinary venting losses during transportation and in-use, equivalent to a rate of 1-2% of container volume per day. As a consequence, most helium is permanently lost within one-year, as the gas literally exits the Earth's atmosphere. Recycled helium volumes are insignificant, although some large users have onsite recovery and reuse systems.

Helium plays a pivotal role in advanced technologies; however specialized handling requirements and time-constrained logistics bring unique complexities to the helium value chain. Overall volumes are relatively small compared to other resource commodities and a limited number of producers control supply. More coordinated efforts across the supply chain from suppliers to end-users may support reliable global helium supply and sustainable access to this critical resource.

Plant-level transformation and joint supply-demand decarbonization pathways of China's steel industry

Sunday, 2nd July - 17:45: MFA case studies 1 (B0.25 KOG)

Xin Tian [1], *Shuntian Xu* [1]

1. Beijing Normal University

Steel is deeply embedded in the socioeconomic system as an essential material base, but the steel industry is extremely carbon-intensive, recognized as a " hard-to-abate " industry that jeopardizes the climate goals. Holding nearly half of the world's steel production capacity, China has recently focused on capacity optimization policies such as "de-overcapacity." Decarbonization of steel involves both capacity optimization and production technology advancements and is influenced by socioeconomic drivers such as demographic changes and consumption patterns. Existing studies on decarbonization pathways of the steel industry pay insufficient attention to socioeconomic system modeling, overlook the discussion of supply-demand relationships in capacity optimization, and lack data on high-resolution steel flows in the design of mitigation strategies. This study develops a city-level dynamic material flow analysis model for steel in China from 1990–2060, in which we quantified the steel consumption demand under population aging based on a queue element population model and consumption survey data. Combining production equipment data, we further analyze the carbon emission impact of each node in the chain of "consumption, capacity optimization, and production." The results indicate a declining trend in steel consumption demand, but with a high uncertainty (0.1–0.9 Gt in 2060). The impact of socioeconomic drivers is noteworthy and could lead to more extreme changes in the consumption demand under different scenarios, such as an accelerated drop or a significant rebound. In the CO_2 reduction analysis, we find that decarbonization pathways in the steel industry are mainly determined by the retirement speed of long-process equipment and are affected by the demand system. We further analyzed some supply-demand balancing strategies and their induced emissions, revealing the interaction among environmental goals, choices of low-carbon technology pathways, and equipment retirement priorities during capacity optimization. Moreover, we explored the spatial distribution planning of short-process plants using multi-objective optimization and found that with the arrival of the "steel scrap age," the focus of China's steel industry will shift from northern China to eastern and southern coastal regions where scrap and demand are abundant, while the green energy-rich northwest region may also become a hot spot for short-process steel plants. Through an in-depth analysis of the demand system and supply-demand relationship, this study bridges the weak points in the supply-demand chain of steel decarbonization research and presents a more detailed overview of carbon neutrality pathways in China's steel industry. Our spatially refined simulations of steel consumption, scrap generation, and trade provide a solid basis for the design of plant-level mitigation strategies. The findings provide new insights into industrial low-carbon transition under profound socioeconomic changes.

LCA case studies 2

Evaluation of Climate Impacts of Dietary Patterns Using Different Nutritional Functional Units: a Case Study of Canadian Provinces

Sunday, 2nd July - 16:30: LCA case studies 2 (B0.31 KOG)

***Basak Topcu* [1], *Goretty Dias* [2]**

1. University of Waterloo, 2. University of waterloo

Affluence is shifting diets towards more meat consumption, with higher environmental impacts, and is resulting in overconsumption of protein, as well as calories relative to recommended amounts that can result in obesity and related non-communicable diseases. Assessment of environmental impacts and nutritional aspects together is needed for a better understanding of the sustainability of food systems. To shift towards sustainable diets that have low impact and high nutrients, the environmental and nutritional aspects must be evaluated simultaneously. Diet life cycle assessment (LCA) is used widely to determine the environmental impacts of various dietary patterns (DPs) but has mostly been used in Europe, and infrequently in the USA. There are only three studies focused on Canada, and none have evaluated the regional DPs in Canada.

In LCA, one of the key elements is the functional unit, which is the unit used to compare products with the same functions. To date, the most commonly-used functional unit in diet LCA studies is caloric intake, but by considering only one function of food which is to provide energy, macro and micronutrients required for healthy people are ignored. A few diet LCA studies have applied nutritional aspects in functional unit using various nutritional quality indices, which estimate the nutritional content of a DP using different macro and micronutrients. The findings showed mixed conclusions in the evaluation of the environmental and nutritional impacts of the same DP. In addition, these studies mostly evaluated hypothetical diets formulated by researchers. Thus, the purpose of this study is to evaluate the global warming potential (GWP) of DPs based on various nutritional functional units, using average food intake in ten Canadian provinces.

We quantified the GWP of the DPs of ten Canadian provinces using the following functional units: (i) energy intake, (ii) Nutrient Rich Foods Index 9.3 (NRF 9.3); and (iii) Healthy Eating Food Index-2019 (HEFI-2019). Canadian regional DPs are determined on actual food intake from the 2015 Canadian Community Health Survey Nutrition for 20,111 participants across Canada. Based on the preliminary results, the selection of nutritional functional unit affected the climate impacts of DPs. Specifically, the provinces with the lowest and highest GWPs shifted substantially when analyzed per calories vs nutritional quality indices. In British Columbia, the GWP per 2000 calories had the seventh highest GWP, while the GWP per NRF 9.3, and HEFI-2019 had the lowest GWP. The association between the GWP and NRF 9.3 and HEFI-2019 demonstrated all provinces had a GWP per 2000 calories above 2050 climate targets and had an average nutritional score. The contribution of foods to GWP and nutritional quality indices showed that across all provinces there is a potential to lower the GWP and increase the nutritional quality of DPs by consuming more plant proteins and less animal proteins. These findings highlight that performing a sensitivity analysis on nutritional functional unit is needed to present robust and reliable conclusions on comparing climate impacts of DPs. In addition, substantial work is needed to determine the most appropriate and relevant approach to simultaneously evaluating the nutrition and environmental aspects of DPs to provide a science-based approach to determining strategies for shifting towards sustainable and healthy diets that meet 2050 climate targets.

REDEFINING NIGERIA'S RESIDENTIAL BUILDINGS IN THE FACE OF HUMAN DEVELOPMENT AND CLIMATE CHANGE CRISES

Sunday, 2nd July - 16:45: LCA case studies 2 (B0.31 KOG)

Chibuikem Nwagwu [1], ***Sahin AKIN*** [1], ***Edgar Hertwich*** [1]

1. Norwegian Univ. of Science and Technology

Nigeria, Africa's most populous nation, boasts of having one of the strongest and largest economies in Africa, with its economy largely dependent on crude oil and natural gas exports. In its Nationally Determined Contributions, Nigeria pledged an unconditional 20% reduction in Business-As-Usual emissions by 2030, though a 45% reduction is achievable with financial assistance, technology transfer, and capacity building. However, limited research, lack of awareness, and poor compliance with existing regulations make it difficult to make relevant policies to meet these targets. The existing building regulation is itself vague with respect to climate change adaptation or mitigation. Estimates by the Global Alliance for Buildings and Construction (Architecture2030 project) show that the global building floor area will double by 2060, with most of the floor area to be added to the existing stock in Africa. OECD projections show that Africa's urbanization rate is expected to cross 60% by 2050. By 2020, Nigeria recorded a total of 44.5 million residential dwellings, marking a 33% increase in the dwelling stock within four years based on 2016 estimates. One major problem of rapid urbanization is the expected rise in emissions, energy, and resource use from different sectors, especially the residential sector. Given the possibility of infrastructure inertia, it is important to model the dwelling stock and estimate the baseline energy and resource consumption and assess future scenarios of development for the country. The study acknowledges the robustness of existing research involving archetype models to estimate energy and material consumption. Thus it uses statistics, peer-reviewed literature, and local expert opinions, to organize the required data for archetype development. After collecting the data, the work applies a bottom-up approach to develop different building archetype models using DesignBuilder. This work proceeds to determine the Nigerian residential building stock's baseline energy and material consumption using BuildME, a framework to calculate building material and energy consumption. Additionally, it converts energy and material consumption to carbon emissions by using relevant emissions factors via life cycle analysis. The work is finalized by developing retrofitting and passive strategy scenarios to aid stakeholders in deciding the best climate change mitigation and adaptation options. To the best of our knowledge, this is the first comprehensive study focusing on Nigerian building stock that takes into consideration a wide variety of archetypes (bearing in mind different climate, architectural, and economic characteristics) and their resource consumption along with their related greenhouse gas emissions.

Embodied Carbon of Buildings – Review of Recent Policies and A case-study

Sunday, 2nd July - 17:00: LCA case studies 2 (B0.31 KOG)

Rahman Azari [1]

1. *Pennsylvania State University*

Buildings are responsible for 30% of global greenhouse gas emissions through their operation (i.e., heating, cooling, lighting, and powering) and 11% of emissions through construction. Building decarbonization has therefore focused on reducing both operational carbon and embodied carbon of buildings. Building Embodied carbon - the global warming potential of a building over its complete life cycle from raw material extraction and manufacturing of building materials and products to building construction, maintenance, and demolition – has received significant interest in the past few years as part of building decarbonization efforts to limit climate change. The present paper reviews the recent policies and challenges in North America to regulate embodied carbon in buildings. The paper also reports on a building case study in which the design team was assigned to limit the building embodied carbon to no more than 277 kg CO2-eq per square meter of floor area. The goal was achieved through close collaboration of the project team members consisting of engineers, architects, contractors and suppliers, sustainability consultants, and other key stakeholders. The team used life cycle assessment and embodied carbon modeling in an iterative process to assess and minimize embodied carbon. The embodied carbon was minimized in the project by replacing the concrete structure with a hybrid timber-concrete structure, specifying low-embodied carbon with high fly ash content, and using mineral wool insulation materials.

Improving the sustainability of the construction sector – Applying streamlined LCA in the planning process of timber houses

Sunday, 2nd July - 17:15: LCA case studies 2 (B0.31 KOG)

***Josef Huber* [1], *Magnus Fröhling* [1]**
1. Technical University of Munich

Context: The building sector is one of the most important economic areas, representing 10 % of the Gross Domestic Product (GDP) worldwide in 2014 and employing over 100 Million people (Dong und Ng 2016). On the other hand, the construction industry accounts for 36 % of the global energy demand and was responsible for 37 % of the energy-related CO_2 emissions in 2020 (United Nations Environment Programme 2021). Therefore, action towards more sustainable building activities and the assessment of efforts are crucial to reach set goals. In the practical case of planning, data availability is an essential restraint to assessment activities. For the provision of reliable results, the data basis has to be reliable, too. This, however, is naturally only the case in an advanced status of planning. Still, the more advanced a planning process is the more difficult it is to implement major changes to it, for example due to the results of a sustainability assessment. To overcome this so called 'participation paradox' (Hirschner 2017) we propose the following approach in order to advance sustainable development in construction.
Method: Accompanying a real planning process with so called 'streamlined LCA' helps us to deal with limited data availability but also provide helpful insights into the environmental performance of the planned building structures (Beemsterboer et al. 2020). We apply the approach to three timber frame buildings (two storeys, no basement, freestanding single or two family homes) which are designed by three timber construction companies from Germany. Our method contains a feedback loop, which mirrors back the results from the assessment of the first draft to improve the sustainability of the design. To identify the most important starting points we combine a contribution analysis with the MCDM method 'TOPSIS' to rank the components of the building according to their overall impact on the environment. In a second assessment step, we evaluate the impact of our adaptions.
Results: The outcome shows that the highest impacts result from concrete, metals (e.g. aluminum window frames), processed timber products (e.g. OSB-boards or MDF-boards) and the insulation materials (e.g. mineral wool or PS-panels). The components with the biggest impacts are the foundation, the roof and the exterior walls. Accordingly, we proposed changes in the type of foundation (strip foundation instead of base plate), the insulation materials (e.g. cellulose instead of mineral wool) and evaluated the replacement of processed timber products by different alternatives (e.g. gypsum fiberboards replacing OSB-boards) with the companies. After the application of the feasible changes to their drafts, the overall environmental impact is reduced by 13 – 20 %. Single impact categories like climate change show higher reduction (between 21 and 32 %) whereas others like 'land use' experience an increase by up to 31 %. However, together with mineral resource consumption, this is the only impact category, which increases because of our changes. All the 16 other impact categories provided by ReCiPe 2016 could be improved for the three cases.
Impact: With the development and application of our approach to the selected cases, we contribute to more environmentally friendly construction activities making use of streamlined LCA. This is achieved by improving the design and planning of buildings already in an early phase of the planning process. Major and important changes in terms of sustainability can be made more easily applying our methodical approach

Minimizing biodiversity trade-offs arising from hydroelectricity production using Life Cycle Assessment

Sunday, 2nd July - 17:30: LCA case studies 2 (B0.31 KOG)

Sif de Visser [1], ***Francesca Verones*** [1], ***Martin Dorber*** [2]

1. NTNU, 2. Norwegian Univ. of Science and Technology

Hydropower is currently the leading renewable energy source for electricity production and plays an important role in providing flexibility, which is needed for a reliable, future energy system (International Energy Agency, 2021). Expansion of hydroelectricity production is expected in future energy scenarios (Zhang et al., 2022) and thus remains important to achieve the United Nation's sustainable development goals on affordable and clean energy and climate action. However, hydropower expansion conflicts with the SDGs for life on land and clean water due to biodiversity trade-offs. The topic of this presentation is to balance the synergies and trade-offs between the different sustainability goals arising from hydroelectricity production.

Life Cycle Assessment (LCA) is a tool used for strategic decision-making and can contribute to a better understanding of the environmental impacts of hydropower compared to other energy sources. To date, hydropower has mostly been studied as case studies within the field of LCA, but biodiversity impacts on hydropower are seldomly considered. The biodiversity trade-offs associated with hydropower development concern freshwater, marine and terrestrial species and arise in all life cycle stages. Dorber et al. (2020) were the first to apply Life Cycle Impact Assessment models for the impacts of land use change, water consumption and methane emissions arising in the operational life cycle stage of hydropower plants.

Our aim is to use LCA to conduct a global impact screening of planned and possible hydropower locations on a global scale. To this end, a framework is developed to consider the remaining impact pathways such as river fragmentation, water level regulation of reservoirs and sediment trapping. Hydropower dams lead to fragmentation of freshwater habitats and infrastructure such as access roads results in terrestrial habitat fragmentation. Water level regulation can result in stranding of species. Sediment trapping has multiple consequences, such as turbid water, altered food webs and coastal erosion.

Dorber, M., Arvesen, A., Gernaat, D., & Verones, F. (2020). Controlling biodiversity impacts of future global hydropower reservoirs by strategic site selection. *Scientific Reports*, *10*(1), 21777. https://doi.org/10.1038/s41598-020-78444-6

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Life cycle assessment of high-value biochemicals: systematic review and recommendations

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Sunday, 2nd July - 17:45: LCA case studies 2 (B0.31 KOG)

Shiva Zargar [1], ***Qingshi Tu*** [1]

1. The University of British Columbia

The environmental concerns associated with the petrochemical industries resulted in the increased research and development of processes in which bio-feedstock can be converted into chemicals. The term “bio-based” is not always synonymous with “environmentally friendly”, mostly when less well-known impact categories such as water depletion, and land use are considered. Although the environmental benefits of biochemicals are largely unclear, they are gaining prominence due to the strong support of governmental policies and environmental regulations. Hence, understanding the trade-offs and synergies among the production of various biochemicals from an environmental perspective is necessary. Hence, a literature review is conducted to understand the extent to which life cycle assessment (LCA) studies are available for high-value biochemicals, to analyze the LCA methodology used in these publications, to understand the efforts that other researchers have done, and to find out a trend among LCA studies of different biochemicals. This study focuses on the top 30 high-value biochemicals recommended by National Renewable Energy Laboratory (NREL). In total, 65 peer-reviewed publications are found that focus on LCA studies of biochemicals. The results showed that the LCA of 22 biochemicals is available in publications or databases. For biochemicals with no LCA studies, the LCA models need to be created using approaches such as a similarity-based method for proxy selection, process simulation, and theoretical methods. All available LCA studies considered evaluating global warming potential (GWP) and 66% considered evaluating fossil fuel consumption and depletion impact categories. Even though water and land use are important elements in biomass production, they are barely reported in publications. A significant variation in GWP of biochemicals production is observed; such as levulinic acid (ranging from 6.30 to 250 kg CO2 eq per kg levulinic acid), and lactic acid (from -4.20 to 64.50 kg CO2 eq per kg lactic acid). This significant range of results routed in several reasons, including 1) different feedstock, 2) different production pathways (standalone production or in an integrated biorefinery system along with biofuels), 3) different processes (e.g. fermentation, catalyst application, or continuous versus fed-batch system), 4) choice of system boundary such as including distribution location (e.g. abroad versus local), and 5) including or excluding biogenic carbon credit. Overall, most GWP results fall between 0 and 5 kg CO_2 eq per kg target biochemical. For biochemicals having petrochemical counterparts, the comparison results show that there is a significant overlap in GWP results between biochemicals and petrochemical counterparts. It is vital to develop a standardized method in which specific guidance is provided regarding the choice of the system boundary, allocation method, and handling of biogenic carbon to support the creation and comparison among biochemical production and assist decision-makers in choosing the right biochemicals and production pathways to achieve sustainability.

IE education

Drawing conclusions: The power of comics for critiquing and advancing industrial ecology

Sunday, 2nd July - 16:30: IE education (B0.13 KOG)

John Mulrow [1], ***Christoph Hinske*** [2]

1. *Purdue University,* ***2.*** *Saxion University of Applied Sciences*

Introduction:

Industrial ecologists are working hard to advance the science of sustainability through metrics development, better modeling of environmental-industrial processes, and ongoing critique of proposed solutions. Translating this work into meaningful dialogue among science, business, and the public is a perpetual issue. It can seem that the nuances of the academic debate are lost in translation to the public. We see renewable energy promoted as "clean" and "green" while the research community works hard to describe the material footprint of solar and wind technologies. The "circular economy" is promoted as a silver bullet for decoupling impact and economic growth; meanwhile, researchers warn about the circular economy's misleading perpetual motion machine qualities. The sustainability research community wishes for a more effective translation of its findings to support meaningful change.

It is well known that art serves as a translation medium for any successful movement. However, can art help translate the nuances of sustainability or the scientific and ethical issues involved in questioning the circular economy or economic growth? This presentation will discuss the power of simple hand-drawn comics for communicating sustainability science and thorny ethical questions.

Methods:

We will present the co-authors' experience using comics to communicate industrial ecology research.

Christoph Hinske presents the successful effort to provide comics-based abstract summaries of articles in "The Impossibilities of the Circular Economy," – an edited academic volume he co-edited in 2022. The editors employed a professional comic artist to create a visual abstract for each article. This artist worked off of each author's answer to the questions: What would you like a reader to remember after completing your article? If there was a second thing, what would it be?

John Mulrow presents the experience of using hand-drawn comics in teaching and communicating complex economic topics in sustainability - including rebound effects, renewable energy technologies' ecological impacts, and economic growth critiques - through his online comic "Limits to Green." John was the 2nd place winner in ISIE's 2022 Cartoon Competition.

Results & Discussion:

The Impossibilities of the Circular Economy comic website had 26,823 unique visitors and 38,438 page views in 2022. The first estimate of LinkedIn engagement is 20,000+ impressions, 5000+ likes, 1000+ comments, and 150+ re-shares. A detailed analysis is still pending.

Several foundations named the comic as the main reason for approaching us about conducting further work on the circular economy. Organizations from Malaysia, China, Italy, Spain, and Germany asked if they could translate the comic at their own expense. Nevertheless, the most impressive aspect is how activists, academics, and policymakers are beginning to own the content of the images because they can; they are creative commons.

The Limits to Green comic has seen the most engagement on topics at the intersection of global equity and national/individual "sustainability." For example, a simple comic questions whether nations with robust recycling infrastructure are sustainable. One skeptical character holds up a map of trade-based carbon footprint per-capita, showing a correlation between high carbon footprint and robust recycling. John uses Limits to Green comics mostly in the classroom to invite debate and provide an on-ramp for discussing difficult conundrums in sustainability.

Our presentation will invite ideas on partnering with artists in scientific communication and it will also stimulate discussion on the difficult contradictions and conundrums that sustainability science must learn to communicate to a wider audience.

Racial Inequalities in Undertaking Doctoral Study in the UK: A Qualitative Analysis at Newcastle University

Sunday, 2nd July - 16:45: IE education (B0.13 KOG)

***Oliver Heidrich* [1], *Sebih Oruc* [1], *Rebekah Puttick* [1], *Michelle Palmer* [1], *Gail de Blaquiere* [1], *Hayley Fowler* [1]**

***1.** Newcastle University*

ONE Planet offers cohort-based doctoral training at Newcastle and Northumbria Universities in the north-east of England, UK.[1] The PhD programme develops independent researchers with the key skills in industrial ecology from Climate and Climate Change, Earth System Processes, Anthropocene to Environmental Informatics to deliver sustainable transdisciplinary responses addressing intensifying global change. Although the UK maintains high rates of student enrolment to postgraduate research programmes, fewer students from minoritized ethnic groups transition to doctoral level studies when compared to white students.[2] The undergraduate degree awarding gap between white students and those from minoritized ethnic groups is one element that impacts the student pipeline to doctoral study[3]. Aspects of advertisement and recruitment strategies may also be unintentionally racialized [4].

This research explores the perceptions of students who have been through (or are considering entering) the recruitment process for a PhD in the environmental sciences, contributing to the discourse surrounding roots of low representation of minoritized ethnicities in any doctoral study. Through focus groups and 1-on-1 interviews, the study has collated evidence from 18 participants of minoritized ethnicity currently studying or researching in the environmental sciences. Through semi-structured interviews we gauged lived experiences and perceptions of doctoral degrees, considerations to undertake a doctoral degree, and if relevant, their experience of the application process.

Speaking to students from undergraduate to postgraduate level, the research recorded a range of perceived barriers and concerns in advancing to PhD study. In terms of the educational journey, we find that although there are concerns regarding the racial diversity of faculty, student bodies, and university spaces, minoritized students viewed socio-economic status or class as an additional and oftentimes more important barrier to enter, or feel as not “belonging” in, an academic space. Although there are multiple reasons for the low representation, this study reveals that people who are at the intersection of disadvantaged race, gender, religion etc., face more obstacles. Female identifying participants displayed the greatest degree of awareness with respect to intersectional identities. Lastly, almost all students expressed a shared view that barriers were structural and socio-economical rather than about Newcastle University. We therefore recommend that a holistic approach that takes both structural and institutional issues into account is needed.

We propose inclusive co-creation of marketing and supportive pre-application processes for a future PhD journey in Industrial Ecology and related areas. We demonstrate this using the ONE Planet recruitment cycle as an example and show how educational journeys should be informed by these insights to try and reduce the socio-economical barriers. Our ambition is to use this evidence-driven and research-based approach to achieve transformative change in the number of successful applications from minoritized ethnic groups to widen environmental sciences.

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2. Office for Students - Students Characteristics Data (2021). Available at: https://www.officeforstudents.org.uk/data-and-analysis/equality-diversity-and-student-characteristics-data/

3. Doku and Amos, 2019: Black, Asian and Minority Ethnic student attainment at UK Universities: #Closing the Gap. Available at: https://www.universitiesuk.ac.uk/sites/default/files/field/downloads/2021-07/bame-student-attainment.pdf
4. (Illing, S. (2019. 16 Feb.). How Capitalism Reduced Diversity to a Brand. Vox, 16 Feb. 2019. Available at: www.vox.com/identities/2019/2/11/18195868/capitalism-race-diversity-exploitation-nancy-leon)

Teaching Industrial Symbiosis at Delft University of Technology

Sunday, 2nd July - 17:00: IE education (B0.13 KOG)

Paola Ibarra Gonzalez **[1]*****, Jaco Quist*** **[2]*****, Dimitrios Xevgenos*** **[3]*****, Gijsbert Korevaar*** **[1]**

1. *Technical University Delft,* ***2.*** *TU Delft,* ***3.*** *Delft University of Technology*

Industrial Clusters are responsible for some of the main environmental and social related problems such as water, air and soil pollution. This regional concentrations of interconnected industries, suppliers, service providers and institutions not only affect their co-located area but its surroundings including nature and adjacent urban areas. Implementation of concepts such as sustainability, industrial ecology and industrial symbiosis play a major role in accelerating the transition to a sustainable society and circular economy through the development of Eco-industrial Parks. Their potential and benefits associated to their implementation should not be considered as a prevention strategy but instead implemented in initial stages of design. Therefore, these concepts should be introduced in education programs to raise awareness among engineers, business, economic, and social science students among others. A higher impact can be achieved if educated students already familiar with these concepts. Providing them the skills, tools and methods to identify improvement opportunities and develop symbiotic and sustainable case studies could drive its implementation. The Leiden University-TU Delft interdisciplinary Industrial Ecology Master program aims to achieve this goal through the 10 study credits project course "Integrated Project: Industrial Systems", which builds on earlier courses on environmental analysis, societal metabolism, innovation-governance-transitions, system design and social science methods, and how the project course integrates from these courses. This work aims to introduce the framework developed by the course lecturers, which consists of 10 phases implemented to real case studies, industrial clusters located in different parts of the world. Phase 1, refers to the understanding of the current operation of a specific Industrial cluster and identifying success and fail factors related to previous studies done on symbiosis and circularity. Phase 2, consists on the mapping and classification stakeholders and identifying their main objectives, main problems and proposing a research question. Phase 3, emphasizes the use of design methods, such as the Multilevel Design Method and Natural Step, and the development of a sustainable indicator framework for iterative assessment of potential improved scenarios. Phase 4, 5 and 6 are focused on the assessment of potential improvements in terms of energy, resources and water, respectively. The assessment includes qualitative analysis of the proposed improvements considering the set of sustainable indicators selected, followed by screening of relevant indicators and quantitative assessment of each scenario using the Best Worst Method, which is an advanced multi-criteria decision-making method. The scenarios are compared and the most sustainable ones for energy, water and resources are selected. In Phase 7, each scenario of improvements in terms of energy, resources and water are integrated and an Eco-Industrial park is proposed. The proposed Eco-industrial park is further quantitatively evaluated using the indicators selected and it is compared with the base case scenario. A trade-off analysis is performed and the implications of their potential implementation are assessed. In Phase 8, the role of the stakeholders in the implementation is addressed and illustrated using a power/interest grid. In Phase 9, an implementation plan is proposed including establishing a timeline, defining expected outcomes, setting roles and responsibilities for each stakeholder and visualizing the strategic plan with a roadmap. The final phase (10), wraps up the findings of the work. The paper links to the industrial symbiosis and EIP literature, discusses content results by the student groups, as well as learning results, and how it could be further developed.

How can Industrial Ecology contribute to making the world more sustainable?

Sunday, 2nd July - 17:15: IE education (B0.13 KOG)

Ichiro Daigo [1]

1. The University of Tokyo

Industrial Ecology studies the relationship between the environment and the socio-economic system by analyzing the stocks and flows of resources and energy in human activities. Firstly, we analyze the stocks and flows of resources and/or energy in scope to recognize the systemic relationships between society, the economy, and the environment. Some studies also quantify services, social impacts, or well-being associated with those physical stocks and flows. Besides understanding those relationships, our studies aim to reduce the physical stocks and flows, increase the efficiency of the system in scope, or predict the possible risks in the future. Industrial Ecology has a history of more than two decades. We are sure that we can contribute more to making our society sustainable based on our knowledge and further research. This study would like to encourage discussions on possible paths of contributions to businesses, policy, consumers, and technological development, derived from the outcomes in IE studies.

When enough knowledge of the systemic relationships on the target system is not available, we analyze the stocks and flows of resources and/or energy in scope. This stage can be recognized as “Understanding of Phenomena.” So far, especially in the early years of the history of IE, many researchers have tried to understand the phenomenon, such as drawing material flow diagrams in MFA studies and calculating a carbon footprint of products in LCA studies.

And then, based on the “Understanding of Phenomena,” there are three different directions for further analysis, which provide helpful information for various purposes. The first direction is “Optimization.” Optimization is a general topic in engineering fields. Instead of a specific process, we can propose an optimal solution in a more holistic system. After clarifying the quantity and quality of secondary resource supply and tolerance for each demand category, we can theoretically optimize the recycling system. Such optimization can provide new possible recycling paths. “Optimization” can contribute to tangible measures in systems in scope.

The second direction is “Elucidation of the Mechanisms.” Some systemic relations can be expressed in a mathematical formula. If the relation is formulated in a quadratic function instead of a linear one, it can predict a highly sensitive reaction to the parameter change. For example, based on the time-series change of in-use stock per capita for base metals, the mechanism of demand in base metals is elucidated as an accumulation of material stock in use, which results in the stock-driven model as a prediction model for future metal demand. “Elucidation of the Mechanisms” may contribute to future prediction and effective control or regulation.

The third direction is “Creation of the Indicators.” Eco-labeling systems and environmental product declaration systems are obvious examples in which some criteria are referred to with a threshold. Recycled contents and end-of-life recycling rates are well-known indicators related to material circularity based on MFA studies. As a sophisticated example, the average time of recycling is stochastically calculated, which could be proposed by MFA studies. “Creation of the Indicators” can contribute to effective communication and monitoring for legislative and business activities.

Here, it is concluded that IE studies start with “Understanding of Phenomena,” and conduct “Optimization,” “Elucidation of the Mechanisms,” or “Creation of the Indicators,” depending on the expected contributions based on our motivations. I hope to have further directions and possible paths for our contributions.

A stepwise approach to teaching about wicked problems in industrial ecology

Sunday, 2nd July - 17:30: IE education (B0.13 KOG)

Stefano Cucurachi [1]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden

The courses that industrial ecology scholars and lecturers teach are closely connected to global challenges and wicked problems (see e.g. Wells (2012)). These are interrelated in complex ways and can hardly be solved or treated only with specialized knowledge within one discipline (Jerneck et al. 2011). Instead, the urgency of such global challenges requires students of industrial ecology and sustainability to embrace complexity, be critical of shortcuts, use systems thinking to stress-test easy wins, and be open to approaches that simultaneously integrate multiple viewpoints, subjects, or interrelations. Many academics have underlined the importance of these aspects, particularly of complexity, in sustainability education (see e.g. Davis and Stroink (2016) and Pipere (2016)).

This contribution focuses on a four-step approach that can support industrial ecology and sustainability lecturers to handle complexity and wicked problems when structuring individual lectures, as well as courses. The approach is structured as follows:

Step-1. Identifying the origin and magnitude of a challenge. Teaching for sustainability requires approaches that aim at seeing a wider perspective and the details simultaneously (see also Willamo et al. (2018) on this matter). Introductory generalist lectures (see also Boersema and Reijnders (2009)) focusing on sketching the problem and understanding its origin help students to get a global view on the origin and magnitude of a sustainability challenge. Such generalist knowledge is also aimed at providing the viewpoint from multiple disciplines and stakeholders, which is fundamental to tackle wicked problems (Spangenberg 2011).

Step-2. Unpacking and comprehending complexity. The complexity of sustainability challenges and related socio-ecological systems can be overwhelming, and it may be challenging for students to formulate research questions and positions, unless they are able to subdivide a problem into more manageable components. Unguided learning, guided in-class activities, and even support from peers help recognizing such components, and to comprehend complexity (see also Pipere (2016) for a classification of the main features of complex systems in sustainability education).

Step-3. Identifying interconnections. No sustainability challenge can be solely explained by how the identified individual components operate independently from one another; Willamo et al. (2018) use the term holism to define such an approach to the complexity of such challenges. The more interconnected parts there are in a system, the more complex the system is. Sustainability challenges have wide spatial and temporal impacts, may radically change the functioning of socio-ecological systems, and can be the results of long historical developments and/or reach far into the future (Willamo et al. 2018). The identification of potential interconnections, feedbacks, and cause-effect dynamics allows students to look at complexity in a comprehensive manner.

Step-4. Testing the impact of solutions at various scales. Students learn that the challenges they analyze have multiple possible formulations, all of which are bound to have trade-offs. There is no one solution that would work at all scales. The concept of such multi-level perspective (Geels 2005) is central to sustainability research and education. For instance, students should be able to assess the impacts of a potential solution at the local, national, and global level and to analyze also the interactions between the levels. Students should also develop the ability to communicate complexity, interconnections, and solutions to a variety of stakeholders using an understandable language.

This contribution will further elaborate on the above and open up the discussion and exchange with fellow lecturers.

The role of community-based learning in teaching about industrial ecology and sustainability in the context of engineering education: A case study from the field

Sunday, 2nd July - 17:45: IE education (B0.13 KOG)

Andrea Hicks [1]

1. *University of Wisconsin-Madison*

Industrial ecology and sustainability education have evolved over time, as this relatively new discipline has emerged and has been refined. Courses engaging with these topics are often found in engineering departments, and feature project or problem-based learning (PBL) commonly with an industrial partner. This provides students the opportunity to apply the topics that they have learned in class in a real-world situation, complete with the constraints and uncertainties inherent in practice. Community-based learning (CBL), a combination of service learning and PBL, allows students to not only apply the material from a sustainability course, but also to do so in service of a community partner. This work presents an analysis of a multi-year effort in teaching a CBL course on the topic of industrial ecology and sustainability in a North American context. Knowledge probes are utilized to quantify student preparation for the course and confidence in knowledge gained during the course in a longitudinal manner. Meanwhile, evolving student reflection is utilized to assess the impact of how the CBL element of the course influenced student thinking about the role of sustainability and industrial ecology within engineering education. The findings suggest that applying CBL to industrial ecology education has the potential to further enhance student learning experiences, while also providing a valuable service experience.
The use of student reflection allowed a deeper dive into understanding the impact and value of the students' experiences in this course. Multiple students mentioned that although sustainability had been discussed in passing in multiple other courses and the idea that it was important had been impressed upon them, this was the first time they really understood how to apply those concepts in a quantitative manner. They felt that by applying major tools of sustainability and industrial ecology, such as life cycle assessment, material flow analysis, life cycle costing, etc. that they had a much firmer grasp of the concept that they would take forward with them into their professional careers.

Industrial Symbiosis 1

The growing reach of industrial symbiosis

Sunday, 2nd July - 16:30: Industrial Symbiosis 1 (B0.16 KOG)

Marian Chertow [1]***, Koichi Kanaoka*** [2]

1. *Yale University,* ***2.*** *Center for Industrial Ecology, Yale School of the Environment, Yale University*

In 1989, Frosch and Gallopoulos shared the idea, in their seminal article *Strategies for Manufacturing*, that "effluents of one process could serve "as the raw material for another process" in what came to be known as industrial ecosystems. At the same time, the industrial symbiosis at Kalundborg was emerging, demonstrating that by sharing resources and reducing waste, water, and energy use, industries can work in harmony while simultaneously reducing their environmental impact and cost.

By 2018, over 800 peer-reviewed articles about industrial symbiosis had been published, enabling the cataloging of 89 industrial clusters in 21 countries (1995-2018) for which information on individual synergies were reported. The first Industrial Symbiosis Research Symposium was introduced in 2004 at Yale and, through ISIE and other sponsors, these symposia were held for 16 consecutive years until the pandemic came. The symposia locations included 4 times in Europe, 4 times in Asia, 6 times in North America, one time in South America and one time in Australia.

A prominent development is that both public and private institutions have become much more interested in industrial symbiosis. The World Bank is quite active now with industrial symbiosis and expects to promote industrial symbiosis in over 300 eco-industrial parks, mostly in the Global South.

This spring, we offered an Advanced IE Seminar class at Yale titled Global Approaches to Industrial Symbiosis. We had high level conversations with active IS scholars and practitioners in places such as Cape Town, South Africa, EU, Iceland, Israel, Australia, and South Korea. Here are some of our findings:

1. Technological innovation is becoming an essential driver for connecting formerly incompatible enterprises in industrial ecosystems, giving rise to a more sophisticated, complex model of industrial symbiosis networks: "industrial symbiosis 2.0".

2. Industrial symbiosis is being adopted as a cooperative *business model* rather than just a practice that increases operational efficiencies through by-product exchanges and collective use of infrastructure while decreasing environmental damage (Bakas 2023).

3. Discussion about the future of IS can go in many directions. One example is the vast advances in chemistry and biology enabling the conversion of a growing number of waste streams that can that can be converted into useful products.

A business value framework for industrial symbiosis

Sunday, 2nd July - 16:45: Industrial Symbiosis 1 (B0.16 KOG)

Murat Mirata [1]***, Axel Lindfors*** [1]***, Marianna Lena Kambanou*** [1]

1. *Linköping University*

Industrial symbiosis (IS) refers to business partnerships involving secondary material, water, or energy flow exchanges or utility and service sharing. Although IS is commonly recognized and promoted as a process creating business values for the involved actors, knowledge on what kind of values are created, and how, remains scattered and possibly incomplete. In the context of IS, the business value can be expressed as the sum of benefits an actor may receive from a synergistic relationship minus the sacrifices made to obtain the benefits. That knowledge on business values of IS remain unstructured and incomplete is problematic because without wider considerations as to what business values can be created through IS, the concept may receive sub-optimal support from both businesses and policy makers. Therefore, this research aims to present a framework that captures the wide range of business value propositions of IS.

The framework was developed based on a synthesis of literature and investigations of existing and developing IS practices. The literature review included 459 articles; each detailing one or more IS cases, and focused on how business values are described, identified or captured therein. For the investigations of IS practices, 41 interviews were performed covering over 60 IS cases, including operational and terminated practices as well as those under development or discarded during development. The interviewees described the types of business value that influenced decision-making during initiation, development, implementation and termination phases. By combining and synthesizing the findings from the literature review and the interviews, a framework was created where business value propositions are aggregated into four major categories: Costs, Revenues, Risks and Soft values.

Apart from well-documented costs—such as those linked to waste management fees, input purchase and transport—a wider range of cost items influenced by IS practices are listed under Costs, including some newly identified ones, such as costs for rents, training new staff and creating new safety procedures. The Revenues category include earnings from sale of residuals and the main products receiving price premiums for improved quality features enabled by the IS (such as the main product's environmental performance increasing). Several of the items in this category have received little or no attention in literature, such as the IS removing production bottlenecks to allow for increased production of main products and that residual owners may receive a share of revenues from sales of the final products, even if the residual owner has not been involved in valorising the residual flow. The Risks include both mitigation and increases of risks due to IS activities, which reportedly played a crucial role in company decision-making. Finally, Soft Values includes a diverse range of benefits and sacrifices that the companies mentioned as enabled by IS. These included mostly qualitative outcomes, such as innovation capabilities and attractiveness to new employees.

This systematic framework can advance research, for example, by highlighting understudied IS values, by guiding studies on the interplay between different value dimensions and by serving as a basis to study if and how different values are considered in IS development decisions. Furthermore, the framework can advance business practice by assisting in more comprehensive identification of IS business values and thereby enabling better-informed decision-making. Finally, it can assist in negotiations of relationship governance terms, including pricing and compensation mechanisms.

Developing curated Eco-Industrial Parks: A scoping review and framework

Sunday, 2nd July - 17:00: Industrial Symbiosis 1 (B0.16 KOG)

Leonie Schlüter [1], ***Hamid Bekamiri*** [1], ***Lucia Mortensen*** [1], ***Lone Kørnøv*** [1], ***Allan Næs Gjerding*** [1]

1. *Aalborg University*

Literature on sustainability in industrial areas is diverse, and has been spanning different disciplines and concepts, such as eco-industrial parks (EIPs) and industrial symbiosis networks (ISN). Many streams of the research field are highly specialized, and, currently, we are lacking an encompassing overview of the field. This article aims at filling this gap and provides a novel overview of how research addresses sustainability in industrial areas.

The method is characterized by an approach that purposely spans across disciplines and includes a wide range of relevant keywords in the search. It applies a novel bibliometric method to science mapping for filtering and structuring this wide body of literature. This approach is called the Semantic Similarity Score method and it uses transformer models, natural language processing, and graph theory to analyse semantic and conceptual similarity of articles' content (Østergaard et al., forthcoming). By relying on this method, it creates picture of the field, which is based on its content and thereby avoids disadvantages of citations-based reviews (Buschman & Michalek, 2013).

The results of the first part of this study show 1056 scientific articles grouped into communities of semantic similarity. 16 of these communities contain more than 10 articles. It is these larger communities, which can be regarded as groups of publications that represent research specialties within the larger theme of 'sustainability in industrial areas'. Therefore, these were included in the following analysis. In each community, we extracted the most common words based on the c-TF-IDF approach and the 3 most characteristic papers based on their eigenvector centrality. Based on this information we could characterize the communities and identify two main themes:

The first theme concerns pollution & risk in industrial areas and includes 10 communities with 328 articles. The second theme addresses EIP and ISN development and includes 6 communities with 218 articles. The topics and research focus within these themes is analysed. Different perspectives on sustainability that research on industrial areas typically takes emerged through this analysis. Thereafter, connections within and across the communities are shown via co-citation analysis. This analysis points towards unexploited synergies that could arise through connecting distant communities.

A second part of this study includes the in-depth analysis of the second theme, which concerns EIP and ISN development. Taking departure in two identified research communities, a systematic review of articles is conducted, which point towards design recommendations for eco-industrial parks. Leaning on the 8 steps suggested by Jabareen (2009), a model is developed which identifies and discusses critical factors for each phase of the development process. The analysis highlights those critical factors described by literature until now and identifies shortcomings that point to future research avenues.

The contribution of this study is twofold: First, it provides a novel and interdisciplinary overview of research on sustainability in industrial areas. Second, it presents an actionable process design model for the development of eco-industrial park and outlines critical factors for the development process.

A modelling workflow to advance collaboration and sustainability of industrial symbioses

Sunday, 2nd July - 17:15: Industrial Symbiosis 1 (B0.16 KOG)

***Shane Carnohan* [1], *Rickard Fornell* [1], *Lovisa Harfeldt-Berg* [1], *Andrew Simons* [1], *Elin Wallin* [1], *Andreas Nicolaidis* [1]**

1. RISE Research Institutes of Sweden

Industrial symbiosis initiatives are on the rise globally (Henriques et al., 2021) due to the potential contribution IS may have across multiple dimensions of sustainability (Martin & Harris, 2018). However, the main benefits revealed in current practice are focused on the short-term reduction of emissions, waste and development of economic value and job creation compared to a current reference point (Lütje & Wohlgemuth, 2020). There is an intrinsic lack of assessments connected to long-term values and the dynamics involved in developing symbiosis initiatives and, simultaneously, recognition of the complexity and potential for cascading problems (Chopra & Khanna, 2014; Durst & Zieba, 2020) among participating firms has led to increased focus on analyzing the various sources of risks facing IS-networks, e.g. through simulation modelling methods (Yang & Zheng, 2020) and empirical methods (Parker & Svantemark, 2019).

As part of the EU Horizon 2020 project, CORALIS, we have developed an integrated modelling workflow to address technical feasibility of material and energy flows in proposed IS (using static thermodynamic modelling), evaluate scenarios and perform uncertainty analysis (system dynamics, SD) and estimate impacts (life cycle assessment, LCA). This work also contributes to current gaps found in recent literature, pertaining to (1) tools and (2) stakeholder engagement. A review of IS modelling studies by Demartini et al. (2022) revealed agent-based (AB) modelling to be the dominant method applied to, in contrast, modelling studies with a sustainability focus tended to use hybrid modelling, combining system dynamics (SD) with discrete event simulation (DES). This analysis therefore appears to point towards opportunities to expand the IS modelling methods currently in circulation. Results from another EU Horizon-2020 project, SCALAR, support the opposite perspective- suggesting that additional tools are not likely to support managers working to expand IS practices (Vladimirova et al., 2019).

Interestingly, the review by Demartini et al. (2022) does not discuss which modelling methods may be appropriate to facilitate stakeholder participation, despite recent research that has recognized the need to improve awareness and information sharing among actors (Lütje & Wohlgemuth, 2020). This aspect was highlighted by the SCALER project, which argued that highly-skilled intermediaries and change agents can play a significant role in aligning tools properly within IS formation processes (Vladimirova et al., 2019). Indeed, the role of knowledge exchange and participatory process within IS is crucial to consider in light of the role of mental models in shaping decision-making (Blokland & Reniers, 2021). At the same time, it is an opportunity for the IS modelling community to address current risk management challenges (e.g., (Durst & Zieba, 2020; Wassénius & Crona, 2022).

The tension between these two research gaps motivates the overall aim of the modelling workflow, which is to leverage the demonstrated effectiveness of the participatory application of SD (Scott et al., 2016; Voinov et al., 2018) as an integrator for both the technical functionality of IS and the economic, ecological and social aspects of the broader system (e.g., Durst & Zieba, 2020). This should enable a transformative approach to IS development, where joint visions for the IS initiative are defined, and then different pathways explored based on a backcasting approach. By learning from sustainability science and developing hybrid workflows risk analysis can be enhanced, so that sustainable IS can be achieved.

Drivers of the Evolving Coal Gangue Power Industrial Symbiosis in China: a comparison with Kalundborg

Sunday, 2nd July - 17:30: Industrial Symbiosis 1 (B0.16 KOG)

Wenting Jiao [1]***, Lei Shi*** [2]***, Ruitong Zhao*** [1]***, Changhong Li*** [1]***, Fangqin Cheng*** [1]

1. Shanxi University, 2. Nanchang University

The uncovering of industrial symbiosis of Kalundborg in Denmark has promoted rich actions worldwide to improve environmental and economic performance of regional industrial system through exchanging wastes and by-products. The evolutionary pattern and its drivers of industrial symbiotic network are crucial research questions in the field of industrial ecology. Chertow and Ehrenfeld (2012) distinguished the phases of sprouting, uncovering, embeddedness and institutionalization of industrial symbiosis network. And Domenech and Davies (2011) delineated three phases – emergence, probation, and development and expansion–of industrial symbiosis, and Paquin and Howard-Grenville (2012) distinguished the phases of pre-network development, earlier network development, and later network development in the study of UK National Industrial Symbiosis Programme. Boons et al. (2014;2016) systemically elaborate the process perspective of industrial symbiosis, and have summarized seven types of industrial symbiosis dynamics, and these dynamics can follow one another over time, constituting different phases of the evolving industrial symbiosis.

Building on these studies, we aim to make the following two contributions to the process perspective of industrial symbiosis. First, industrial symbiosis of Kalundborg, which was evolved around Asnaes power station, is a seminal exampler in the field of Industrial Ecology. However, scholar still lack the understanding of the characteristics (i.e. types of firms, linkages between firms, structure of the network) of the similar industrial systems that are embedded in different national contexts. Therefore, we select the industrial symbiosis of Pingshuo Coal Gangue Power Station(PCGPS) as our case, which has been awarded China's National Industrial Award in 2018, due to its efforts on energy saving and CO2 emission reduction. We will compare the main structural characteristics of the system with Kalundborg.

Second, both policy facilitation and firms' efforts are two crucial driving factors for the evolution of industrial symbiosis in China, however, the temporal features of these driving factors of different phases of the evolution of industrial symbiosis is unclear, especially in the Chinese context. We aim to add to the understanding of the evolutionary dynamics of industrial ecosystem by investigating the PCGPS case. Main research questions are:

1) How did the industrial ecosystem around PCGPS *evolve, and what are the driving factors over time?*

2) What are the similarities and differences between the industrial symbiosis of PCGPS *and Kalundborg in the aspects of evolutionary patterns and driving factors?*

The main methodology is longitudinal and comparative case studies. For the Kalundborg case, our insights are mainly from literature review. For the case of PCGPS, news reports, firm annual reports, and field work and interviews are the main sources. And we are in the currently analyzing data and drawing conclusions. We are able to present the case of PCGPS and its comparison with Kalundborg in the conference.

From the ground up: designing a greenfield eco-industrial park in rural Australia

Sunday, 2nd July - 17:45: Industrial Symbiosis 1 (B0.16 KOG)

Tim Baynes [1], ***Jacob Fry*** [2]

1. *Australian National University,* ***2.*** *Shrunk Pty Ltd*

We present a prospective material, water and energy flow account for a planned eco-industrial park (EIP) in rural Australia: the Parkes SAP. The site is currently greenfield and surrounded by agriculture and mining industry. We will talk about the technical potential and also some of the path-dependency challenges for developing an EIP literally from the ground up.

Context: The initiation of an EIP can depend on a number of factors, for example, pre-existing or 'keystone' industries with high levels of trust, proximity to transport hubs, technical opportunities for resource exchange or by-product reuse. The State Government of New South Wales has identified at least five regional centres as 'Special Activation Precincts' (SAPs) with the intent to develop industry and local economies outside of the major centres. One such SAP is near the town of Parkes in Central West NSW. The strategy is to co-locate industry that could exchange resources, share infrastructure, services, and circular economy goals. A central part of many eco-industrial parks is an industry that produces energy, whether that be fuels, electricity or (often) heat. The eco-industrial sites at Kalundborg in Denmark and Kwinana in Western Australia, started with coal-fired power plants and oil or chemical refineries. The Parkes SAP is to be developed around accessible, renewable energy sources including a 66MW solar farm on-site that also allows for incidental livestock grazing.

Method: We follow the logic and material balance approach consistent with the EUROSTAT standard (EUROSTAT 2018) but we do not attempt to calculate a complete materials flow account (MFA) including, for example, 'net additions to stock' and 'total material extraction' that would include evaporation of water on-site, or extractions from soil in the intensive agriculture sector. We were guided by the Parkes SAP *Infrastructure and Transport Plan* and the *Parkes SAP Master Plan* in selecting prospective activity on-site and target industries One of the industries we investigate is a 25 MW waste to energy facility and also energy production from anaerobic digestion.

Results: prospective indicative MFA results for the Parkes SAP are based on available techno-economic information and assumptions about scale of operations. This is not a prediction but a presentation of self-consistent estimations for different industries that could be developed at a greenfield EIP. In addition to the MRF, industries including Value-Added Agriculture, Advanced Plastic Recycling, Cold-Chain Storage and Cross Docking, Abattoir and Intensive Agriculture, and the Waste to Energy facility could handle over 800 kilotonnes/year and generate 180 Gigawatt-hours of energy to supplement power from nearby renewable sources. A pet-food manufacturing plant has been recently approved and developed, though its gas supply is currently derived from fossil fuels.

Conclusion: A logistics hub, and the MRF enable some circular economy aspects of the Parkes SAP, but the time course of when different industries are developed, may affect the EIP's efficacy. The use of agricultural bio-waste and other renewable sources could provide a substantial fraction of power needs, but a significant constraint is water supply and use in a location with variable rainfall.

Plastics: MFA

Towards a Comprehensive MFA of Plastic Waste in the developing context – a case study of Chennai, India

Sunday, 2nd July - 16:30: Plastics: MFA (B0.41 KOG)

Sowmya Marriyapillai Ravisandiran [1]***, Nicolas Navarre*** [1]***, Stefano Cucurachi*** [1]
1. *Institute of Environmental Sciences (CML) - Universiteit Leiden*

Mountains of solid waste in landfills and rivers of plastic in oceans have become a symbol of modern society, more so in developing countries.

Asia is responsible for 71% of the world's mismanaged plastics (Neo et al., 2021) with India ranking 12th in the world (Shanker et al., 2022). In contrast, several studies have determined that India has one of the world's highest plastic waste recycling rates, between 40-60% (Shanker et al., 2022). These two seemingly contradictory pictures make India, an interesting choice for a case study on plastic waste management in the developing context.

There are unrecognised warriors in the Global South who have been instrumental in achieving high plastic recycling rates. These are the informal waste workers who work outside the mainstream formal system and collect recyclable material from households, garbage dumps, or even landfills directly. In fact, India owes its successful plastic recycling rate in part to the informal sector.

While there have been studies to quantify the plastic waste management system of India, there is little known about the extent of the contribution of the informal sector to plastic recycling due to the 'invisible' nature of its operations.

This study attempts to expand the existing body of knowledge on the contribution of informal sectors in achieving high plastic waste recycling rates in India, by focusing on the test case of the city of Chennai in South India. In that regard, this paper aims to address the following two sub-research questions related to the plastic recycling value chain: (1) **What are the material flows of household plastic waste along the formal and informal recycling value chain of plastic waste in Chennai, and where do exchanges between the two sectors occur**? (2) **What are the data gaps in estimating the material flows, and the barriers and challenges in building a comprehensive MFA of plastic waste in the developing context**?

To answer the first question, the tool Material Flow Analysis (MFA) is used to estimate the recycling value chain of plastic waste generated in Chennai. The plastic waste flows from the stage of waste generation in households to End-of-Life management are covered. The interplay between formal and informal waste sectors is included wherever present. To obtain data for the MFA model, secondary data from peer-reviewed literature, and other literature like reports, government publications, etc. are combined with primary data collected via field visits and interviews with experts.

Data unavailability is one of the biggest barriers to building a comprehensive MFA of plastic waste management system in Chennai, particularly the contribution of the informal sector. Thus, qualitative data obtained from the interviews about the barriers to data collection and the social issues that keep the system hidden from the outside is used to discuss the second research question. Finally, possible solutions to circumvent these issues are explored to promote the flow of information among internal and external stakeholders to envision a more effective and fair plastic waste management system.

The study highlights the importance of involving informal waste pickers in the plastic waste management process, as they play a significant role in achieving a circular economy through recycling plastic waste. By recognizing the contributions of the informal waste sector, this study also aims to improve the lives of waste pickers and promote their inclusion in the formal waste management sector.

Plastics in the Indian economy: A 20-year update on data, issues and interventions

Sunday, 2nd July - 16:45: Plastics: MFA (B0.41 KOG)

Nargessadat Emami [1]***, Tim Baynes*** [2]***, Katherine Locock*** [1]***, Trinayana Kaushik*** [3]***, Mandavi Singh*** [3]***, Souvik Bhattacharjya*** [3]

1. *Commonwealth Scientific and Industrial Research Organisation,* ***2.*** *Australian National University,* ***3.*** *The Energy and Resources Institute*

Plastic is valued for its flexibility to be utilized in different applications, yet it poses a significant threat to our environment because of mismanaged plastic waste. Every year, almost 300 million tonnes of plastic waste are generated worldwide, however less than 10% of the plastic waste gets recycled. Leaks from plastic waste into the environment can cause substantial problems for terrestrial and marine ecosystems and species, as well as material value loss. Thus, there is an urgent need for a better understanding of plastic flows which can help to identify areas of inefficiency and potential leakage to natural systems. India's compound annual growth in apparent consumption of major commodity plastics has been nearly 7% for a decade. Forecasting material flows is essential for sound policy making on issues relating to waste management. However, a detailed material flow analysis of Indian plastics has not been conducted since Mutha et al. (2006) compiled data from the year 2000. We present a 20-year update, including the current characteristics of plastic production and end use in sectors. There are important and inherent data gaps, notably around the collection and treatment of post-consumption plastic flows and their ultimate fate. Acknowledging these uncertainties, we have established a self-consistent MFA model, based on the available data on Indian national flows for 2018–19, while estimating data where primary sources were unavailable. We use the data and model to quantitatively assess the production, consumption, and fate of plastics in India and comment on the opportunities and challenges of implementing circular economy initiatives with a highly dispersed, heterogenous and partly informal waste management industry. Building on the analysis, the paper discusses a number of strategies for redirecting the plastic system to more circular pathways. This work would be of interest to a broad scientific community, particularly those interested in both policy and technological aspects of the plastic industry in India. Key to this is the national scale, mass-balanced, self-consistent and transparent nature of this approach. It will thus allow this analysis to be a key tool for identifying interventions likely to have the most impact on India's mismanaged waste flows.

A Markov chain model for evaluation of the global plastic waste management system

Sunday, 2nd July - 17:00: Plastics: MFA (B0.41 KOG)

Elijah Smith [1], ***Melissa Bilec*** [1], ***Vikas Khanna*** [1]

1. University of Pittsburgh

The global nature of the plastic waste crisis has become immediately apparent through recent revelations regarding the international plastic waste trade network and the global effects of plastic pollution. Many countries export a portion of their plastic waste, with developing countries most often accepting plastic waste from developed countries. Further, there is a disparity in the waste management capacity amongst trading countries resulting in over 2 million metric tons of extra mismanaged plastic waste in 2010. Plastic waste management must therefore be studied at the global level, where the role of each country, management subsystem, and their interconnections are considered. Plastic waste trade and recycling are two major subsystems whose impacts remain poorly understood. Researchers have identified the need to understand the interconnection between plastic waste trade and mismanagement. However, there is a lack of quantitative estimates that study the impact of trade on plastic waste mismanagement at the global level.

This work presents a discrete-time absorbing Markov chain model of the global plastic waste management system to clarify the role of each subsystem and compare the current system to alternative scenarios. Specifically, we look at four alternative scenarios representing elimination of plastic waste trade and quantify the extra burden that trade places on management system of individual countries. We also model five additional recycling scenarios representing improvements in recycling systems, their impact on the global plastic waste management system, and their efficacy in reducing permanent disposal rates. We found that the impact of eliminating plastic waste trade could be either positive or negative depending on how other systems respond to the elimination of trade, optimistically reducing annual mismanagement by 0.3 million metric tons (Mt) and pessimistically increasing it by 1.2 Mt with similar policy-dependent variability at the local level. Analysis of recycling systems showed that highly optimistic improvements to recycling may reduce linear disposal rates by over 30% when synergistic changes are made, suggesting that countries with high mismanagement rates should prioritize the development of sound linear management infrastructure. In addition, analysis of recycling scenarios highlighted the critical importance of collection rates, and that the employment of chemical recycling technologies offer little benefits at current collection rates.

How much mismanaged plastic waste is reaching the oceans? A methodology to estimate mismanaged plastic flows in emerging and developing nations

Sunday, 2nd July - 17:15: Plastics: MFA (B0.41 KOG)

Diana Ita-Nagy [1], *Ian Vazquez-Rowe* [1], *Ramzy Kahhat* [1]
1. *Pontificia Universidad Católica del Perú*

Plastic accumulation in world oceans has gained international attention in recent years given the increasing flows of macro- and microplastics into the marine environment. Sources, pathways, and derived environmental impacts are currently being studied to understand the complex interactions during plastic waste transportation to the sea. In this context, rivers have been identified as debris corridors allowing transportation of mismanaged waste for long distances. However, there is also evidence of waste accumulation in river basins, suggesting they can also act as sinks due to a series of natural or manmade barriers, such as hydropower plants or agricultural canals. Other factors, such as location of waste disposal sites, urbanization or waste pickers, among others, can also influence the final flows entering water bodies. Thus, assuming a uniform and continuous transportation of waste through rivers towards the ocean may signify an oversimplification. Moreover, the role of rivers in marine plastic accumulation gains importance in emerging and developing nations in which municipal solid waste (MSW) is not correctly disposed of in sanitary landfills. In these cases, open dumpsters are usually poorly managed and can easily become an important source of plastic release. In this context, the current study proposes a methodology to estimate plastic release to the ocean, considering a more detailed characterization of each river basin, including natural attributes and manmade constructions that may act as barriers or boosters for this release. For this, the methodological framework characterized the basin and quantified the plastic waste entering the ocean based on two main mechanisms: i) observation through field studies; and ii) data gathering related to the basins assessed. Thereafter, an empirical formulation was proposed which considers the most crucial barriers, as possible natural or anthropogenic sinks. The methodology is exemplified using a case study for the Region of Piura, in northern Peru. The results show, for year 2018, that 14,118 metric tons of plastic waste were estimated, on average, to have been released to the ocean, 7,883 metric tons for the lower scenario, and 26,049 metric tons for the upper scenario. These values translate into a per capita rate range from 4.2 to 13.9 kg plastic/year with an average of 7.5 kg plastic/year. Our results, when compared with the existing literature, demonstrate more conservative estimations. The methodology is presented as a useful tool that can be easily applied to develop more accurate mismanaged waste dissipation along different compartments. However, future research should analyze in further depth the dissipation rates avoided through the abovementioned barriers through sampling techniques.

Circular Economy for Plastic Consumption in Australia: Opportunities and Challenges

Sunday, 2nd July - 17:30: Plastics: MFA (B0.41 KOG)

Sadegh Taskhiri [1] ***, Heinz Schandl*** [1]

1. *Commonwealth Scientific and Industrial Research Organisation (CSIRO),*

In Australia, about 2.54 Mt or 101 kg per capita of plastic waste was generated in 2018-19 of which packaging represents 26% of the total volume of plastics used. Only 18% of all plastic packaging is recovered for future use. The Australian government has a target of zero landfill disposal of plastic packaging by 2025. A circular economy approach is now widely recognised as the only solution to manage the plastic pollution problem through redesigning the entire plastic system. In the literature, three strategies including elimination, reuse and material circulation (recycling, composting, and substitution to a non-plastic material) of the plastic packaging have been discussed. However, the implementation of the above strategies is very challenging. Extended Producer Responsibility (EPR) is one of the policies to facilitate the development of above strategies. In the EPR approach, the producer is responsible financially and sometimes operationally to manage the end of life of the products and packaging. The literature discusses successful case studies which implemented EPR for groceries and supermarkets products in EU and Canada. We present a material flow analysis for plastics in Australia and identify priorities for improving the circularity of the plastics value chain. We discuss the technology and innovation potential of designing out waste and recovering of materials and the use of secondary materials in manufacturing and construction and the policy levers that would facilitate a transition to a circular economy of plastics. Taken together, a good understanding of the size of problem, the required innovation and the policy, economic and behavioural adjustments can support Australia's roadmap to the sustainable management of plastics.

Opportunities for improving the circularity of plastic polymers. A Norwegian case study.

Sunday, 2nd July - 17:45: Plastics: MFA (B0.41 KOG)

Miguel Las Heras [1], ***Golnoush Abbasi*** [1], ***Marina Hauser*** [1], ***Kees Baldé*** [2], ***Evert Bouman*** [1]

1. Climate and Environmental Research Institute NILU, 2. United Nations Institute for Training and Research (UNITAR)

The use of plastics in society has grown twenty-fold since its introduction in everyday life and is expected to continue this growing trend thanks to its versatility, durability, and low cost. Production of plastic relies almost entirely on fossil fuels, and global plastic recycling rates are below other broadly used materials such as paper or steel. It presents significant environmental challenges along its life cycle, including pollution, waste, and harm to wildlife. The Norwegian government has introduced a set of strategies for a circular plastic economy by 2050. This new Norwegian plastic strategy calls for increased recycling, reducing waste, and promoting sustainable production and consumption. Variations in production and consumption patterns may alter the plastic waste composition, impacting recycling strategies and demand for raw materials. Effective strategies for increasing the circularity of plastics in industry and consumption need to consider potential feedback loops. Thus, it is crucial to have a systemic understanding of the life cycle of plastics and quantify the current presence of plastics in society and their end-of-life pathways.

Here, we present a dynamic probabilistic material flow analysis (DPMFA) of the seven most used polymers (low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET) in Norwegian society from 1950 to 2050. A total of 40 individual product categories were examined and aggregated into nine industrial sectors. The model considers the whole life cycle of plastic, from the trade of raw materials to waste collection and end-of-life treatment, and provides a comprehensive overview of the consumption of each polymer type. The DPMFA model was used to understand the evolution of the composition of plastics flows and stocks in production, consumption, and waste. The effects of the national plastic strategy have been analyzed from 2020 until 2050 through a set of forecasting scenarios. Impacts and opportunities generated by interventions such as stricter recycling targets, improved waste sorting, eco-design directives, and expanded producer responsibility (EPR) are discussed for these scenarios.

The results estimate that 620 ± 23 kt or 114 kg/capita of these seven plastic polymers were put on the Norwegian market in 2020. The outcomes of the model also show the amount and polymer composition by industrial sector and application. The model predicts the fate of future plastic flows in Norway, from production to waste. It provides invaluable insight into the potential effects of the planned implementation of production regulations and waste management strategies towards 2050. It gives policymakers a ground for devising effective circular economy plans to successfully confront the growing problems associated with plastic waste in the future. This research also sets a basis for comparing the life cycle impacts of different recycling strategies, allowing to include the mitigation of GHG emissions into the decision-making process.

If Norway is to transition towards a circular plastic economy, systems must be introduced to facilitate a systematic classification of products according to their suitability for recycling and potential to be made of recycled materials. This will enable sustainable recycling of plastic waste into new products, limit production from primary sources, lower consumption, and prevent waste generation.

Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (Part 1)

Lower energy and materials demand for net-zero GHG futures for industry – a critical review of the potentials, strategies, and modelling approaches required for transformative insights

Monday, 3rd July - 09:00: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (Part 1) (A1.44 KOG)

Dominik Wiedenhofer [1], ***Jan Streeck*** [2], ***Barbara Plank*** [3], ***Alessio Mastrucci*** [4], ***Bas van Ruijven*** [4], ***Benigna Boza-Kiss*** [4], ***Gamze Unlu*** [4], ***Leila Niamir*** [4], ***Volker Krey*** [4], ***Arnulf Gruebler*** [4], ***Maria Fernanda Godoy León*** [5], ***Yiyi Ju*** [6], ***Jonathan Norman*** [7], ***Leticia Magalar*** [8], ***Nuno Bento*** [9], ***Frauke Wiese*** [10], ***Elena Verdolini*** [11], ***Joni Jupesta*** [12], ***Akimoto Keigo*** [12], ***Ayami Hayashi*** [12], ***Stefan Pauliuk*** [13]

__1.__ University of Natural Resources and Life Sciences (BOKU), __2.__ University of Natural Resources and Life Sciences, Vienna, __3.__ University of Natural Resources and Life Sciences, Vienna., __4.__ International Institute for Applied Systems Analysis, __5.__ University of Ghent, __6.__ The University of Tokyo, __7.__ University of Bath, __8.__ CENERGIA - Centre for Energy and Environmental Economics, Energy Planning Program, COPPE, UFRJ, __9.__ ISCTE - Universitary Institute of Lisbon, __10.__ University of Flensburg, __11.__ Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (EIEE/CMCC), __12.__ Research Institute of Innovative Technology for the Earth (RITE), __13.__ University of Freiburg

Sustainable development and climate change mitigation require a deep structural transformation of global industrial production to rapidly reduce industry's multiple environmental impacts. Industry also needs to transform to meet rapidly changing demand patterns for industrial output required for sufficient service provision and societal wellbeing around the world. Model-based insights are crucial for effective policy design and evaluation of supply- and demand-side strategies, to understand potentials, synergies, and co-benefits, but also trade-offs, limits and problem-shifts associated with such transformation processes.

A special challenge lies in understanding the implications of changing future demand patterns for industry development. Scenarios including, but not limited to, effective demand-side reductions are of specific interest, because they will lead to lower overall energy and material demand in some world regions in the future, reducing the need for risky future technology deployment centered on, for example, negative emissions or geoengineering. In this manner, achieving net-zero emissions and meeting 1.5-2°C climate targets will become more feasible in the required time frame.

In this review, we take an integrated and comprehensive demand-supply perspective on the industrial transformation. We review the growing number of recent studies and modelling approaches, which explore transformative low energy and low-materials demand (LEMD) scenarios towards net-zero GHG emissions. We synthesize key principles and crucial considerations for LEMD scenarios with high service provision and wellbeing, which should ideally be addressed by industry modelling to fully show the potentials of supply and demand-side strategies. Via an expert-driven process, we identify and review nine modelling traditions which operate at a scale and scope necessary for LEMD modelling, which are equilibrium/neo-classical economics, non-equilibrium/post-keynesian economics, partial equilibrium modelling, macro-econometric forecasting, environmentally extended input-output analysis, life cycle analysis, material and energy flow analysis, system dynamics, agent-based modelling, as well as eclectic calculator tools.

We review the recent state-of-the-art of industry modelling across these traditions, assess their current research frontiers, and showcase findings on the potentials of strategies aimed at industrial decarbonisation, energy and material efficiency, and a more circular economy. We have currently identified about 100 relevant modelling studies for in-depth assessments & review. We synthesize recommendations for model development, industry transformation, interdisciplinary collaboration, and informing as well as assessing policy.

For deep transformation assessments, industry cannot be conceived as an end-use sector anymore, but indus-

try output should be seen as meeting demand for services and wellbeing. To comprehensively assess various supply- and demand-side strategies, the economic and physical/technical description of industries need to be made consistent, and industry modelling should be more systematically linked to non-monetary service provision indicators and their contributions to wellbeing.

We preliminarily conclude that these developments can happen via interdisciplinary modelling approaches, open model interfaces and databases, and soft coupling of models. This will enable increasing comprehensiveness, consistency, and robustness of model-based assessments of industry transformation in response to LEMD futures, thereby more systematically supporting policy and action.

This submission is linked to the special session proposal “BRINGING INDUSTRIAL ECOLOGY AND THE CIRCULAR ECONOMY INTO INTEGRATED ASSESSMENT MODELS”

EXPLORING THE POTENTIAL OF DEMAND RESPONSE PARTICIPATION IN JAPAN'S INDUSTRIES BY 2050: SOFT-LINKING IAM AND IO

Monday, 3rd July - 09:15: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (Part 1) (A1.44 KOG)

Yiyi JU [1]***, Tao Cao*** [2]***, Firdaus Nur*** [3]***, Baixin Li*** [1]

1. Waseda University, 2. The University of Tokyo, 3. Kyoto University

Virtual power plants (VPP) aggregators provide energy management services to the holders of distributed energy resources. Those resources include photovoltaic power generation facilities and energy storage facilities in industries, buildings, and other sectors. As a result of managing those flexible loads, the overall electricity supply-demand imbalance can be narrowed, the application rate of renewable energies may increase, and national-level GHG emissions can be reduced.

Japan has pledged to achieve 100% GHG emission reduction by 2050. To estimate the demand response potential in industry processes (e.g., load shedding/shifting in electrolysis processes, EAF steel making, usage of devices providing cooling/heating, etc.) and how this can contribute to the GHG reduction, we carefully mapped the processes in industry sub-sectors (steelmaking, paper & pulp, cement & concrete products, and petrochemical sub-sectors) with those in the national Input-Output table extended in industry sub-sectors and a VPP business sector (table IONGES, compiled in our previous work Washizu et al., 2022) for the calibration in the baseline year. We then investigate the demand response potential in the long-term climate pathways by an open-source Integrated Assessment Model (GCAM, partial equilibrium energy system with exogenous industrial energy demand in non-agriculture-related sub-sectors). This study may contribute to a better understanding of the role of private actors and demand-side mitigation options in the achievement of carbon neutrality.

(Join as a potential presenter for the session: Integrating industrial ecology into MACRO-ECONOMIC assessment models)

The CIRCular Energy Economy model: reconciling Industrial Ecology and Economic concepts

Monday, 3rd July - 09:30: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (Part 1) (A1.44 KOG)

Darius Corbier [1], ***Laurent Drouet*** [1], ***Valentina Bosetti*** [1]

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Special Session : BRINGING INDUSTRIAL ECOLOGY AND THE CIRCULAR ECONOMY INTO INTEGRATED ASSESSMENT MODELS

Abstract

The decarbonization of our production processes and consumption of products and materials have a key role to play in achieving climate targets. Switching from a linear to a circular economic system that aims at increasing resource efficiency and reducing Green House Gas (GHG) emissions can address this challenge. The integration of circular economy poses many challenges to the IAM modelling community. Specifically, the integration of physical material flows, thermodynamics limits, and waste flows into IAM models is key to assess the potential of the circular economy in mitigating GHG emissions. Unequivocally, the controversy that opposed Georgescu-Roegen/Dally and Solow/Stiglitz the last century has never been as important as today as the climate modelling community is trying to bridge the gap between industrial ecology and economic concepts. The *CIRC*ular *E*nergy *E*conomy (CIRCEE) model addresses these challenges by developing a stylized dynamic model that will assess how the interaction between circular economy strategies and its enablers can reduce future GHG emissions and increase resource efficiency. The stylized model will serve as a modelling starting point for the IAM community and will help mapping circular economy strategies into the existing climate scenarios.

Methods

The CIRCEE model is a stylized dynamic general equilibrium model that keeps track of physical material and waste flows/stocks and incorporates key elements of industrial ecology. The model integrates the interactions between circular economy strategies and its enablers as a powerful tool to decrease GHG and increase resource efficiency. The economic agents are the following: heterogenous households, key economic sectors (refined virgin material producing firm, recycled material producing firm, final good firm, sharing/collaborative firm, and a repair services firm), and a public authority. Households choose to consume different types of goods (non-durables, semi-durables, and durable goods), and different types of services (home-produced energy services, sharing services, or repairing services). The public authority implements circular economy policies, levies taxes, and makes public expenses. The production structure of the economy is economically and physically consistent. It considers key thermodynamic limits, such as the impossibility of 100% recycling and repairing, a minimal material balance constraint, a thermodynamic efficiency condition, etc. Besides, for now, the model is country-specific, though it considers trade flows between the domestic economy and the rest of the world. The study of trade flows is important, as imports and exports of goods may have different material intensities.

The CIRCEE model is soft linked to the IAM model WITCH from the European Institute on Economics and the Environment (EIEE) to assess the overall GHG mitigation potential of circular economy strategies.

Studies

The CIRCEE model will focus on countries that may become relatively less material-intensive in the long run thanks to the implementation of key circular economy strategies and new business models. CIRCEE's studies will provide a broad perspective on the socio-economic-climatic implications of a circular economy. The policies under study are the following:

- Promotion of capital and durable goods repair

- Promotion of green product design to increase the longevity of goods and the recyclability of goods
- Incentives to substitute in favor of recycled materials
- Incentives to reduce waste generation (e.g., EPR schemes)
- Promotion of the Sharing Economy
- (Promotion of the second-hand market)
- (Promotion of R&D investments to increase material productivity and quality of recycled materials)

Resource efficiency at the national level

Monday, 3rd July - 09:45: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (Part 1) (A1.44 KOG)

Jonathan Norman [1], *John Barrett* [1], *Sam Betts-Davies* [2], *Rachel Carr-Whitworth* [1], *Alice Garvey* [1], *Elliott Johnson* [1]

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Resource efficiency strategies (also referred to as material efficiency and encapsulating the principles of the circular economy) are increasingly recognised as an important component of decarbonisation pathways. Here we define resource efficiency strategies as providing a similar or improved service with a reduced requirement for materials or product manufacture, and consequently lower energy and/ or emissions impacts. This includes opportunities relating to material substitution, lightweighting products, replacing private ownership with service provision (also referred to as the sharing economy), improved product lifetimes and increased reuse and recycling.

The UK MRIO is an environmentally extended multi-regional input-output model developed by the University of Leeds to provide the official consumption-based emissions accounts for the UK. A methodology has been developed to assess the impact of resource efficiency strategies using the UK MRIO. This allows the full supply chain impacts of resource efficiency strategies to be captured, within a consistent whole economy framework. Further, it allows the impacts to be presented in terms of both territorial and consumption-based accounting. This method and the results of a recent assessment of the potential for resource efficiency to impact territorial and consumption-based emissions are presented here.

These assessments of the potential for resource efficiency have been used by UK policymakers in informing decarbonisation pathways, users include the Department for Energy Security and Net Zero, the Department for Environment, Food and Rural Affairs and the Climate Change Committee. There are however several challenges related to pursuing resource efficiency through policymaking at the national level, illustrated by the current study. The first of these relates to the impact of such strategies on different accounting metrics. The highest relative and absolute savings through resource efficiency are seen in consumption-based emissions for the UK, however territorial emissions are the basis of existing targets and of principal interest to policymakers. The second challenge relates to the ability of national level policymaking to influence different parts of a product's (international) supply chain and the third challenge the disconnect between the aim of resource efficiency to consume less and policymakers desire for continued economic growth. Each of these are discussed and recommendations made.

The impact that national level action can have on resource efficiency is further explored through several scenarios that assume different levels of "influence". For any resource efficiency strategy there are two principal actors: the producer (or supplier) of the product and the consumer (or customer). Considering unilateral action at the national level it may be possible to pursue strategies where either of these actors are within the region of interest. For example, if lightweighting a vehicle it may be that domestic consumers demand (or regulation requires) lighter vehicles and both domestic and overseas suppliers meet this demand. Alternatively, it could be that domestic producers of vehicles are required to lightweight vehicles and these are supplied to both domestic and overseas markets. Here several scenarios around the "influence" that the UK could have on resource efficiency strategies are explored, with the impacts on both territorial and consumption-emissions calculated. This provides insights into the role of national level policymakers in achieving improved resource efficiency and recommendations are made around the need for international cooperation and the use of suitable metrics to track improvements.

Modeling the energy-transport nexus in the Israel's economy using the MESSAGE model: combining bottom-up and top-down approaches

Monday, 3rd July - 10:00: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (Part 1) (A1.44 KOG)

Vered Blass [1], ***Ayelet Davidovitch*** [2], ***Paul KISHIMOTO*** [3], ***Rotem Izak*** [1], ***Anat Tchetchik*** [4]

1. Tel-Aviv University, 2. Tel Aviv University, 3. International Institute for Applied Systems Analysis, 4. Bar Ilan Univerity

Future mass deployment of Alternative Fuel Vehicles (AFV) requires investment in infrastructure and technology. In this research, we analyzed the future of the energy-transportation market based on a passenger transport representation embedded in an innovative energy national techno-economic model. This representation derived from a unique behavior model of passengers' preferences. The study motivation is to understand penetration of the different technologies and their adoption impact. We first focus on modelling the consumer behavior, demand patterns, and the factors affecting the transition to using such vehicles. Further, the study examines the diffusion consequences for various AFVs and their implications on national energy systems and the environment.

We approach a novel set of behavioral parameters using a research design that connects bottom-up (micro) data through choice models to a (macro) model of the entire energy-economic system. At the micro level, we applied multi-segment choice modeling methodology for identifying consumer preferences to better estimate demand. At the macro level, we modified the integrative MESSAGEix energy model application to include a detailed transportation energy with a logit-based choice model, used for economic and environmental scenarios analysis.

The MESSAGEix-Transport (MTix) is a global integrated assessment model (IAM) based on dynamic bottom-up technology-based optimization model designed for medium to long-term energy planning and policy analysis. In this research, the model was updated to present the Israeli Energy market (MTix_IL) incorporating the transport consumers' choice modelling. The transport sector contains vehicle choices mechanism, which are influenced by both financial and non-financial considerations.

We present the results form our main scenario, defined in accordance with the Israeli Ministry of Energy policy. The scenario includes increasing the share of renewable energy and shifting to electric vehicles, while eliminating coal from the energy mix for power generation.

The results indicate about the significant environmental and economic parameters, including emission reduction aspect, which is a key parameter in evaluating the impact on the environment. This study provides a comprehensive analysis of the transport energy-sector, utilizing both techno-economic as well as behavioral aspects. The study can be adopted to other regions and countries based on the same integrated model with adjustments for their specific behavior and segments characteristics.

Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1)

Urban Carbon Inequality

Monday, 3rd July - 09:00: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1) (A0.51 KOG)

Klaus Hubacek [1]***, Giovanni Baiocchi*** [2]***, Kuishuang Feng*** [2]***, Yuli Shan*** [3]

1. *University of Groningen,* ***2.*** *University of Maryland, College Park,* ***3.*** *University of Birmingham*

Inequality is a major challenge. Global wealth is concentrated amongst a relatively small elite, while hundreds of millions still live in extreme poverty, and half of the global population lives on less than US$3.50 in purchasing power parity per day. This inequality is reflected in differences in contribution to carbon emission or carbon responsibility. There are significant differences in carbon footprints of households even within the same income group depending on a wide range of factors and location. Lots of these emissions happen in urban areas with more than half of the global population living in cities, and projected to further increase in the future. The majority of human activities, 80% of global GDP, 60% to 80% of final energy consumption and 75% of energy related carbon emissions are in cities. Therefore, cities are central to climate change mitigation. Given the fact that that global supply chains play a significant role in urban activities, cities predominantly rely on their hinterland to supply the resources they need. Different accounting approaches and system boundaries may lead to significant differences in emission patterns of cities and may greatly change the interpretation of success of cities carbon mitigation efforts. Accounting for global supply chain effects of different consumption patterns, we will investigate carbon inequality in rich versus poor countries, urban versus rural, as well as providing a deep dive into lifestyles and associated carbon footprints at fine spatial resolution based on market segmentation approaches to express relationships between geodemographics and consumer behaviour. Our findings support the notion that carbon mitigation strategies should move beyond a ‘one-size-fits-all’ approach and account for community specific differences, lifestyle and consumer preferences, and demographic characteristics at fine spatial scale.

Towards a Nexus Science for Zero-Carbon Cities with Health, Climate Resilience, and Equity Co-benefits

Monday, 3rd July - 09:20: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1) (A0.51 KOG)

Anu Ramaswami [1]

1. *Princeton University*

This talk will draw upon a recent review article led by author Ramaswami, to appear in the Annual Reviews of Energy and the Environment, on developing a new nexus science that enables transition toward zero carbon cities while advancing health and wellbeing, social equity and climate resilience co-benefits. The paper argues that decarbonization models alone do not suffice, rather, they must be integrated with design for wellbeing, health (WH), equity (E) and climate-resilience (R), co-benefits, particularly at the urban scale where most of the world's people live. However, science is nascent on the linkages between zero-carbon pathways and WHER outcomes. This paper presents a transboundary urban metabolism framework, rooted in seven key infrastructure and food provisioning systems, to connect urban decarbonization strategies with WHER outcomes. Applying the framework along with a literature review, the paper reports evidence on the nexus with decarbonization to be strong for health. However, the nexus linkages between zero-carbon pathways and resilience are uncertain and could yield positive and negative linkages, needing further research. And, further, intentional design is needed to advance equity, including distributional, procedural, and recognitional aspects. The talk will describe existing nexus linkages and knowledge gaps, and delineate broad parameters of a new urban nexus science to enable zero-carbon urban transitions with WHER co-benefits.

Leveraging Opportunity of Low Carbon Transition by Super-Emitter Cities in China

Monday, 3rd July - 09:40: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1) (A0.51 KOG)

Heran Zheng [1]***, Jing Meng*** [1]***, Dabo Guan*** [1]***, Dan Moran*** [2]***, Kuishuang Feng*** [3]

***1.** University College London, **2.** NTNU, **3.** University of Maryland*

Chinese cities are core in the national carbon mitigation and largely affect global decarbonisation initiative, yet disparities between cities challenge country-wide progress. Low-carbon transition should preferably lead to a convergence of both equity and mitigation targets among cities. Inter-city supply chains that link production and consumption of cities are a factor in shaping the inequality and mitigation, but less considered aggregately. Here, we modelled supply chains of 309 Chinese cities for 2012 to quantify carbon footprint inequality, as well as explore a leverage opportunity to achieve an inclusive low-carbon transition. We revealed significant carbon inequalities: the 10 richest cities in China have per capita carbon footprints comparable to the US level, while half of Chinese cities sit below the global average. Inter-city supply chains in China, which are associated with 80% of carbon emissions, imply substantial carbon leakage risks and also contribute to socioeconomic disparities. However, the significant carbon inequality implies a leveraging opportunity that the substantial mitigation can be achieved by 32 super-emitting cities. If the super-emitting cities adopt their differentiated mitigation pathway based on affluence, industrial structure, role of supply chains, up to 1.4 Gt carbon quota can be created, raising 30% of projected carbon quota to carbon peak. The additional carbon quota allows the average living standard of other 60% of Chinese people to reach an upper-middle-income level, highlighting collaborative mechanism at city-level has a great potential to lead a convergence of both equity and mitigation targets.

Carbon Monitor Cities, Near-Real-Time Monitoring of Daily Fossil-Fuel CO2 Emissions from Cities Worldwide

Monday, 3rd July - 09:52: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1) (A0.51 KOG)

Da Huo [1]***, Zhu Liu*** [2]***, Philippe Ciais*** [3]

__1.__ Tsinghua University and University of Toronto, __2.__ Tsinghua University, __3.__ Laboratoire des Sciences du Climate et de l'Environnement LSCE

Urban areas generate more than half of fossil-fuel carbon dioxide (CO2) emissions worldwide, and many cities are in urgent need of near-real-time emission inventories to timely adjust climate policies and monitor mitigation progress. Unfortunately, such datasets are still lacking for most cities, and existing inventories are mostly at national scale and often lag reality by at least one year. City self-reported inventories also suffer from low reliability due to the lack of peer review. Here we present the Carbon Monitor Cities, a recently developed near-real-time CO2 emissions dataset that provides daily, city-level estimates of scope-1 CO2 emissions from 2019 through 2022 for over 1500 major cities worldwide. This dataset is developed based on an innovative workflow that combines a global harmonized top-down approach and available bottom-up inventories for power, residential, industry, ground transportation, and aviation sectors. Carbon Monitor Cities reduces the time lag of city-level emission dataset to less than 6 months and estimates daily emissions which can help investigate high resolution urban activity-emission dynamics. We find that for most cities, emissions exhibited a significant drop in spring 2020 due to the COVID-19 pandemic, and rebounded in 2021. The daily emissions also highlight the heterogeneous sectoral and temporal responses to lockdowns and daily emission patterns that reveal a city's geographic and socio-economic characteristics. We plan to frequently update this dataset and improve the workflow in the future to better facilitate urban climate policymaking.
(Special session: Urban Climate Action Toward Carbon Neutrality)

Assessment to city-level emissions and peak in China

Monday, 3rd July - 10:05: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1) (A0.51 KOG)

Jinghang Xu [1]***, Yuru Guan*** [2]***, Jonathan Oldfield*** [1]

1. University of Birmingham, 2. Univisity of Groningen

With the pledge to achieve Dual-Carbon goals (i.e., achieving the peak of national CO_2 emission before 2030 and carbon neutrality before 2060), China are taking great efforts to reduce CO_2 emissions. Cities, as important agents of climate change mitigation, are indispensable to realizing the Dual-Carbon goals. Long-time-series emissions inventories for cities are the fundament to make sub-regional mitigation policies. However, the available energy data at the city level varies, making it difficult to compile detailed, accurate, and comparable emission inventories. To fill this gap, our study will compile CO_2 emission inventories of 287 Chinese cities from 1997 to 2020. The inventories encompass 47 socioeconomic sectors and include energy-related emissions from 17 fossil fuels combustion and process-related emissions from cement production. Our emission accounts will be in line with the Intergovernmental Panel on Climate Change (IPCC) administrative-territorial approach. Furthermore, as Chinese cities have huge differences in many aspects, in particular resource endowment, emission patterns, and socioeconomic development, we will investigate the status of emission peaks in different types of cities and explore their hidden driving forces to the emission decline. Our results will show great policy significance with a particular focus on city-level mitigation measures.
This is a submission to the special session “Urban Climate Action toward Carbon Neutrality”.

The Landscape of City-Level GHG Emission Accounts in Africa

Monday, 3rd July - 10:18: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 1) (A0.51 KOG)

Binyuan Liu [1], ***Klaus Hubacek*** [2], ***Riemer Kuik*** [3], ***Lazarus Chapungu*** [4]

1. *Integrated Research on Energy Environment and Society, Energy Sustainability Research Institute Groningen, University of Groningen,* ***2.*** *University of Groningen,* ***3.*** *Univisity of Groningen,* ***4.*** *Institute of corporate Citizenship, University of South Africa*

Cities are important actors in the global challenge of tackling climate change. An important precondition for effective climate mitigation is knowing where emissions occur based on a city-level greenhouse gas emission inventory to guide mitigation action. Yet, most cities in developing countries, in particular African cities, lack that crucial information. Assessing the current state of the development of African cities' inventories could help reveal this shortcoming. In this work, we reviewed sixteen studies and three databases about the city-level GHG emission assessment in Africa and investigated the state of city-level GHG emission assessments in African cities. In total 238 assessments on city-level environmental impact in Africa were found, covering 137 cities in 54 African countries. We find that existing research tends to focus on the more populated cities and South African cities, leaving less populated cities unassessed. Furthermore, 184 assessments are guided by ad-hoc rather than widely used frameworks, which decreases the reliability and comparability. Data scarcity is another quite common problem that African cities are facing for assessment. 158 assessments adopt downscaling to make up for the missing data, which lowers the assessment accuracy. In the end, we propose six approaches to improve African cities' GHG emissions accounts.
This is a submission to the special session "Urban Climate Action toward Carbon Neutrality"

Special Session: Does space Matter? -transition of built environment towards circularity in a spatial context

Circular economy conclusions based on a global analysis on Impacts of urbanisation on construction material consumption

Monday, 3rd July - 09:00: Special Session: Does space Matter? -transition of built environment towards circularity in a spatial context (B0.17 KOG)

Georg Schiller [1], ***Julia Roscher*** [1]

1. *Leibniz Institute of Ecological Urban and Regional Development*

Urbanization is considered a main driver of building material consumption. Nevertheless, statements on links between urbanization and resource consumption remain qualitative. This study aims to globally quantify the links between urbanization and non-metallic mineral resource consumption at the level of nations. Based on hypotheses, we have investigated the relationship between construction material consumption and urbanization and further impact variables. Data were examined using descriptive and analytical statistical methods, by developing step-by-step regression models and representing them in a path diagram. The results show that urbanization alone does not adequately explain consumption of construction materials. Prosperity has a strong impact, too, but also does not have sufficient explanatory power in itself. Only the combination of both variables reveals their complex interrelationships. In principle, more prosperous societies consume more construction materials than less prosperous ones, regardless of the degree of urbanization. With low prosperity, however, material consumption per capita rises with increasing urbanization; with high prosperity, the effect is reversed. Developed societies are the problem today. However, with increasing urbanization and prosperity, dynamically growing societies will dramatically exacerbate the carrying capacity problem in the future. Then again, this is by no means inevitable. Rather, the key is to move from linear to consistently circular models of urbanization. These models must be comprehensive and spatially specified in order to develop sufficient clout in terms of effective resource protection through "circular urbanization". This can be supported by applying regional material cadastres.

Space and place - perspectives on a circular built environment

Monday, 3rd July - 09:15: Special Session: Does space Matter? -transition of built environment towards circularity in a spatial context (B0.17 KOG)

Andreas Blum [1], ***Mustafa Selçuk Çıdık*** [2]

1. *Leibniz Institute of Ecological Urban and Regional Development*, **2.** *University College London*

The circular economy is gaining significant attention in the built environment due to its potential to mitigate negative impacts of growing urbanisation and infrastructure investments by improving resource efficiency. In particular because of the strongly territorialized character of the built environment and the construction industry, the local context must be considered alongside generalized guidelines and regulations to achieve tailored and effective outcomes.

To this end this contribution proposes that space and place – the physical and social dimensions of local constellations – are crucial concepts to consider in developing and implementing circular solutions in the built environment. Physical space refers to the location, natural environment, and geographical characteristics and relations in which circular solutions are implemented, while place – social space – refers to the relationships and networks between stakeholders involved in the implementation process.

By introducing physical aspects like density, proximity, and material availability as well as socio-spatial aspects of divergent interests, power, routines, visions and last not least mutual trust of the various involved actors, this contribution provides a starting point for further discussion of the role of space and place as two crucial dimensions of a circular built environment. Ultimately, a better understanding of the meaning and significance of local physical and social constellations as the context of circularity solutions can lead to the identification of leverages towards more effective and tailored outcomes that benefit the built environment, local construction industry and local communities.

A review of spatial characteristics influencing circular economy in the built environment

Monday, 3rd July - 09:25: Special Session: Does space Matter? -transition of built environment towards circularity in a spatial context (B0.17 KOG)

***Ning Zhang* [1], *Karin Gruhler* [1], *Georg Schiller* [1]**

***1.** Leibniz Institute of Ecological Urban and Regional Development*

Industrialization, population growth, and urbanization are all trends driving the explosive growth of the construction industry. Creating buildings to house people and operate industry, together with building infrastructure to provide public services requires prodigious quantities of energy and materials. Most of these virgin materials are non-renewable, and resource shortages caused by the development of the built environment are becoming increasingly inevitable. The gradually evolved circular economy (CE) is considered a way to ease the depletion of resources by extending service life, increasing efficiency, and converting waste into resources. However, the circularity of construction materials shows heavy regional distinctness due to the difference in spatial contexts in the geographical sense, resulting in the same CE business models (CEBMs) not being adapted to all regions. To optimize resource loops and formulate effective CEBMs, it is essential to understand the relationship between space and CE in the built environment. This paper reviews existing publications to summarize the research trends, examine how spatial features are reflected in the circularity of materials and identify connections between spatial and CE clues. We found that the majority of contributors in this interdisciplinary field are from countries with middle to high levels of urbanization. Further, the case analysis details the material dynamics in different spatial contexts and links space and material cycles. The results indicate that spatial characteristics can indeed influence the circularity of materials through varying resource cycling patterns. Utilizing spatial information wisely can help design locally adapted CEBMs and maximize the value chain of construction materials.

Mapping Storage Infrastructure for a Circular Economy

Monday, 3rd July - 09:35: Special Session: Does space Matter? -transition of built environment towards circularity in a spatial context (B0.17 KOG)

Ling Min Tan [1]

1. *The University of Sheffield*

More than 60% of the UK waste comes from construction, demolition and excavation (CD&E), according to UKGBC. Majority of the recovered CD&E waste is downcycled into products of lower value such as recycled aggregates, and some ends up in landfill. Reuse of waste recovered from CD&E can help to reduce primary material demand and the associated embodied carbon emissions from the extraction, manufacturing, storage and transport of materials. However, a key barrier to reuse of these materials is the lack of infrastructure to store the bulky and heavy building materials that could be reclaimed from CD&E before they have a chance to be reused when the supply and demand are matched. Hence, this project aims to explore how utilisation of storage facilities can improve the uptake of reusable materials from the demolition of buildings. Here in this pilot study we work with major infrastructure providers to identify the type, size, and location of potential storage facilities. This information is used to produce a GIS-map of storage facilities, which is then overlaid with the national transport network to compute the shortest distance between the storage sites by roads and rails. As a proof-of-concept study, this work demonstrates how a network analysis method can be applied to analyse the storage capacity of existing infrastructure in terms of nodal centrality and clustering of the storage sites across the UK. Going forward, collaborations between organisations will aid standardisation and enhance network efficiency for effective resource exchange in the future.

Investigating material recycling possibilities for different geographical scales and temporal windows. Opportunities for the Construction sector

Monday, 3rd July - 09:45: Special Session: Does space Matter? -transition of built environment towards circularity in a spatial context (B0.17 KOG)

***Jonathan Cohen* [1], *Leonardo Rosado* [1], *Jorge Gil* [1], *Maud Lanau* [1]**

***1.** Chalmers University of Technology*

Reusing existing material stocks can significantly reduce natural resource extraction, waste, and the environmental footprint of the construction and demolition sector. However, material reuse in urban areas presents technical, temporal, and geographical challenges. While scientific contributions on increasing material reuse exist, they have mostly overlooked the dynamic and spatially explicit nature of construction and demolition activities.

City planning departments issue permits for new construction and demolition without considering future material availability, which limits the potential for material recycling. This study aims to validate the hypothesis that coordinating the date and location of new construction and demolitions can increase the potential for material recycling.

To achieve this, we used the city of Gothenburg, Sweden as a case study and calculated the material stock of each building using material intensity coefficients for residential properties. Then, we estimated the year of potential demolition for each building by gathering information about its construction and renovation history. By combining these sets of information, we were able to estimate the potential material availability in different locations in the city and in different years.

Overall, this research provides a proof of concept for incorporating the spatial and temporal dimensions of construction and demolition activities to achieve a Circular Economy and sustainability in the construction and demolition sector.

Ex-ante LCA 1

Well-to-Wake LCA of Liquid Hydrogen Jet Fuel

Monday, 3rd July - 09:00: Ex-ante LCA 1 (B0.25 KOG)

T. Reed Miller [1], ***Marian Chertow*** [1], ***Edgar Hertwich*** [2]

1. *Yale University,* ***2.*** *Norwegian Univ. of Science and Technology*

The aviation industry faces a formidable challenge to cap its greenhouse gas emissions (GHGs) given continued growth in passengers and freight. Liquid hydrogen (LH_2) is one of the alternative jet fuels under consideration as it does not produce carbon dioxide upon combustion. We conducted a well-to-wake life cycle assessment of CO_2 emissions and non-CO_2 climate change impacts per passenger-distance for seventeen different hydrogen production routes, as well as conventional jet fuel and biofuels. Six other environmental and health impact categories were also. The Boeing 787-800 was used as the reference aircraft and a range of flight distances were explored. Contrail cirrus contributes a significant fraction of the life cycle climate impacts for LH_2, more so than for conventional jet fuel, showing that research is needed to reduce uncertainty in the case of LH_2. No currently commercial LH_2 fuel pathways offer significant climate benefits over conventional jet fuel and several perform worse. Some novel LH_2 pathways do show considerable climate impact reductions versus conventional fuel, but even with renewable electricity, LH_2 production is not climate neutral.

Life Cycle Assessment of microfluidic devices for point-of-care testing: a comparative analysis of PDMS, paper and PLA

Monday, 3rd July - 09:15: Ex-ante LCA 1 (B0.25 KOG)

Kristie Tjokro [1], ***Stefano Cucurachi*** [1], ***Alina Rwei*** [2], ***Justin Lian*** [1]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden, 2. Faculty of Applied Sciences - TU Delft

Microfluidics is an area of research that studies and designs microminiaturised devices that confine liquids in micro-channels to transport, separate, or mix them. With microfluidic devices, typical laboratory analyses can be miniaturised without sacrificing resolution or sensitivity. Due to the scale of lab-on-a-chip devices, smaller reagent quantities are needed, it is cost efficient, portable, and reduces analysis time. Microfluidic devices are applicable in many fields, such as genetics, molecular analysis, cell biology research, and point-of-care testing. As a field, microfluidics is in its adolescence. While there have been many innovations, there is room for improvement. Varying designs utilising varying manufacturing methods and materials have been developed, but few are optimally designed for large-scale commercialisation. The search continues for a design which can achieve cost-effectiveness, scalability, time-efficiency, high ease of manufacture, high resolution, and widespread applicability.

The most common manufacturing technique for microfluidic devices in laboratories is soft lithography using polydimethylsiloxane (PDMS), an elastomeric polymer. This technique is cost-effective, but PDMS has some limitations, such as unstable wettability and adsorption of small molecules. Furthermore, the master moulds utilised in soft lithography are manufactured in cleanrooms, which are notoriously energy intensive.

The need for cleanrooms, and the fact that PDMS is difficult to recycle, makes the prevalence of PDMS in microfluidics a concern for environmental sustainability. Alternative materials include paper and bioplastics used in 3D printing, like polylactic acid (PLA). These have the potential to circumvent the technological limitations and environmental impacts associated with PDMS microfluidic devices.

To investigate the environmental performance of various microfluidic devices and how they may be improved, a comparative environmental life cycle assessment (LCA) was conducted. The 3 devices studied are: a PDMS device manufactured through soft lithography, a paper device manufactured through wax stamping, and a PLA device manufactured through 3D printing. These devices have the function of detecting glucose in a human sample, and they are portable as they require minimal to no additional instrumentation. The functional unit studied in the LCA is *1 run of detecting glucose in a human sample using 1 microfluidic device*.

The LCA was conducted according to the ISO14040 framework and covered the product systems from cradle-to-grave, thereby including any processes associated with raw material extraction, manufacturing, use, and end-of-life. Brightway2 and the Activity Browser, an open-source program for conducting LCAs, was used as modelling software. The study also considered how scaling up the production of these devices from laboratory-scale to commercial-scale would affect the environmental impacts that can be attributed to each device.

The results show that on the laboratory-scale, the PLA microfluidic device has the largest impact in most impact categories. This can be attributed to the high electricity consumption associated with 3D printing. The paper device performs the best. However, when considering an alternative manufacturing method for commercial-scale production, the PLA device performs best. On this scale, the PDMS device performs worst. Generally, manufacturing processes are the biggest contributors, due to their high electricity consumption. These impacts can be reduced by transitioning to renewable energy sources, or through redesigning the devices.

Researchers wishing to reduce the environmental impacts of their laboratories, or device designers, would benefit from the results of this study. Likewise, this study will be helpful to future research and development focusing on the scaling-up of the manufacturing and recycling of microfluidic devices.

Closing the GHG mitigation gap with measures targeting conventional light-duty vehicles – A scenario-based analysis of the U.S. fleet

Monday, 3rd July - 09:30: Ex-ante LCA 1 (B0.25 KOG)

***Nadine Alzaghrini* [1], *Riddhiman Roy* [2], *Alexandre Milovanoff* [1], *Amir F.N. Abdul-Manan* [3], *Jon McKechnie* [4], *I. Daniel Posen* [1], *Heather L. MacLean* [1]**

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Despite national efforts to increase the adoption of alternative fuel vehicles, the Annual Energy Outlook (2021) projected that conventional gasoline internal combustion engine vehicles (ICEV-Gs) will form roughly 70% of new U.S. light-duty vehicle (LDV) sales through 2050. Fully leveraging the GHG reduction potential of targeted changes to ICEV-Gs can limit the challenges arising from full fleet electrification (surge in demand for critical materials and electricity consumption, infrastructure upgrades, among others).

We analyze the annual and cumulative reductions of greenhouse gas emissions that may be obtained by 2050 from effective policies targeting these combustion engine powered vehicles, using the Fleet Life cycle Assessment and Material-Flow Estimation Model (FLAME). We consider technological, decisional and behavioral solutions that are plausibly available for immediate implementation. Technological pathways include fuel economy improvements, vehicle lightweighting and a greater provision of ethanol blends. Decisional pathways include purchasing decisions related to vehicle size and relative (best-in-class) fuel economy among available models. Behavioral pathways include improvements in driving habits.

We first evaluate the individual impacts of these pathways on the U.S. LDV fleet life cycle GHG emissions from 2021 through 2050, along with their joint impacts – which are not strictly additive. We then determine the reductions in GHG emissions that may be obtained for six scenarios representing different levels of commitment to the proposed pathways wherein 1) ICEV-G are dominant and made more efficient (Slow, Steady and Utopian progress), 2) HEVs become dominant and are improved on (the New Conventional and the New Conventional - Enhanced) and 3) full fleet electrification materializes by 2035.

We demonstrate the transitional and complementary role to fleet electrification that ICEV-Gs can play for the U.S. LDV sector to remain within a CO_2 emission budget consistent with a 2°C climate target. Through the analysis of the individual impacts of the proposed pathways, we show that driver-based pathways such as the use of commercially available, fuel-efficient conventional gasoline models (best-in-class, small-sized or hybrid counterpart) as well as adopting eco-driving practices can lead to substantial GHG emission reductions.

Through the scenario-based analysis, we determine that immediate and aggressive advancement of the best-in-class ICEV-G mix associated with high improvements in fuel consumption through 2050 can lead to the mitigation of almost 95% of the emissions gap consistent with a 2°C climate target. We estimate a limit for the ICEV-G fleet decarbonisation at 40% of cumulative lifecycle emissions from 2021 to 2050 in a very optimistic scenario, which suggests that these measures can complement but not replace the need to develop alternative fuels and powertrains. We then show that effective and diverse mitigation pathways targeting ICEV-G decarbonisation may lessen the need for aggressive fleet electrification rates – reducing the required cumulative electric vehicle sales by at least 10% and extending the target year for full fleet electrification by a minimum of 5 years from 2035.

We conclude with a screening of the International Energy Agency policy database where we show that governments have a wide range of tools at their disposal (regulatory, financial and/or educational) to target each of the pathways considered.

Prospective LCA of Emerging Transportation Systems as demonstrated by the Electrification of a Regional Aircraft

Monday, 3rd July - 09:45: Ex-ante LCA 1 (B0.25 KOG)

Susanne Hanesch [1], ***Liselotte Schebek*** [1]

1. Material Flow Management and Resource Economy, Institute IWAR, Technische Universität Darmstadt

In the transport sector, new technologies need to be developed and their environmental performance assessed in order to ensure a significant reduction in greenhouse gas (GHG) emissions. This poses a challenge in conducting life cycle assessments (LCA) according to the ISO standard, as it requires data acquisition for technologies under development and consideration of future developments. For road transport, numerous new electromobility technologies have been developed, already launched on the market and investigated in various LCA studies. For air transport, on the other hand, suitable concepts for electrified transportation alternatives are only being developed on a laboratory scale at a low Technology Readiness Level (TRL), which is why LCA studies in this field are lacking. Our work closes this gap by presenting a comparative LCA study of different air transport technologies using a 19-seat regional aircraft in short-haul operation and two electrified alternatives.

For conducting the LCA of emerging transportation systems on a laboratory scale, we have developed a method that combines two assessment stages. In the first stage, all relevant input parameters are generated for the LCA results of the reference state. In the second stage, selected input parameters are modified for the LCA results of the future state. In our case study, the data input for the three aircraft types was derived from a computer simulation on design and operation for the area of Germany. From this data, we created a life cycle inventory (LCI) and first performed the reference LCA, which refers to TRL 3 of the emerging electrified aircraft. Then we performed the LCA for the future state, in which not only the electrified aircraft have entered the market, but also the surrounding markets have evolved. The data modification takes into account the technological changes of the aircraft, the upscaling to TRL 9 and the scenario parameters for different time horizons. The integrated scenario approach for the conventional and electrified technologies represents, on the one hand, a possible development state for the near future and, on the other hand, the development into the far future in 2050.

Our LCA results of the different regional aircraft technologies are first derived on the basis of the input parameters generated for the reference state and then separately for the considered changes through the input parameter modification for the future state. It can be demonstrated that, with the inclusion of future development paths, notable GHG emission reductions can already be achieved for the conventional aircraft. While for the electrified alternatives the considered future developments of the electricity mix and hydrogen production have a significant effect on the environmental impacts. As a final outcome of the second stage approach, a technologically and temporally appropriate comparison between emerging and established technologies can be achieved. We claim that it is necessary to always provide LCA results of both stages so that without modifying the LCI in the first stage, the further use of the original LCI data is ensured. Furthermore, by additionally including the second stage, our prospective method allows for a thorough investigation of future scenarios, enabling a robust comparison of possible transportation alternatives to decarbonise the transport sector. This procedure can improve early decision support with regard to further research of emerging technologies in the path to market maturity.

Probability Distribution Analysis of Technical Parameters for Sewage Sludge Management System based on Unit process database

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 10:00: Ex-ante LCA 1 (B0.25 KOG)

Huimin Chang [1]***, Ming Xu*** [1]***, Yan Zhao*** [2]***, Anders Damgaard*** [3]***, Thomas H. Christensen*** [3]

1. *Tsinghua University,* ***2.*** *Beijing Normal University,* ***3.*** *Technical University of Denmark*

Modelling the sewage sludge management system has become a crucial aspect for evaluating and optimizing technologies. However, to make accurate assessments, it is important to generalize sewage sludge parameters as scattered data can hinder model development. Our review of 600 scientific papers found several key parameters, including technical process parameters, composition, transfer coefficients, energy and resource consumption, and pollution emission parameters. The data was standardized and found to mainly follow normal or lognormal distributions, with significant variations.

For the sewage sludge composition around the world, thickened sewage sludge contained 3.3% total solids (TS), which follow lognormal distribution. The average ash content was 32.4% of TS, with 53.3% C, 6.8% N in volatile solid (VS) and 6.7% P, 1.7% K in ash. Other parameters were the lower heating value of 22.1 MJ/kg VS and the biochemical methane potential of 0.25 m^3 CH_4/kg VS. TS content is the core parameter for water removed technology including: dewatering, deep dewatering, bio-drying and thermal drying. The average TS content was 25-30%for mechanical dewatering, 35-40%for deep dewatering, 60% for bio-drying and 90% for thermal drying. Chemical agents used in mechanical dewatering showed values of 5-15 g/kg TS. Energy consumption was low for mechanical dewatering (0.12-0.26 kWh/kg TS) and high for thermal drying (3.8 kWh/kg TS). The biological treatment of sewage sludge in terms of anaerobic digestion and composting was analysed. Biogas production varied significantly in anaerobic digestion, with a correlation between biogas production and degradation of volatile solids. Estimates of VS degradation could not be made due to the presence of organic bulking materials during composting. But The data on energy consumption and recovery was limited, and emissions into the air were scarce. The thermal treatment of sewage sludge has gained interest on incineration, gasification, and pyrolysis. Incineration is an established technology, but tradable data on air emissions is scarce. Energy recovery is close to the amount used for incinerating dried sludge (0.2 kWh/kg TS), but more energy is used for dewatered sludge (1-2 kWh/kg TS). Gasification and pyrolysis are emerging technology with four outputs: char, tar, fly ash, and syngas.

Our review of the available data on sewage sludge treatment technology found that it provides important information on the processes involved, but it is limited in regard to energy consumption and recovery as well as direct emissions. To improve consistency in mass balances, energy budgets, and emission accounts, future research should report data on inputs and outputs in a more comprehensive manner. The variability seen in biotreatment, and thermal treatment technologies requires careful control of experimental conditions to identify optimal operational settings based on desired outcomes. However, the current data is not adequate to make technical decisions. A full inventory should also take into account the management of various outputs, as this is critical to fully understand the impact of sewage sludge management technologies.

Going beyond generic LCA: A framework for mass-deployment of customized semi-automated carbon footprinting

Monday, 3rd July - 10:15: Ex-ante LCA 1 (B0.25 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Marit Salome Rognan [1], ***Guillaume Majeau-Bettez*** [1], ***Manuele Margni*** [1]

1. CIRAIG, Polytechnique Montréal

Advancements in life cycle assessment (LCA) and environmentally extended input-output analysis enable quick, generic estimations of the environmental footprint of almost any type of product and service. To go beyond a generic estimate to an assessment based on actual and specific supply chain data remains too costly and requires significant data sharing between supply chain actors and the LCA practitioner. This, coupled with companies' reluctance to share proprietary information to third parties on their purchases, sales, and emissions, makes it impracticable to assess products and services with specificity. Although the demand for LCA is growing in regulatory applications, such as mandatory corporate greenhouse gas reporting and product carbon footprint disclosures, nearly all upstream impacts are estimated using generic, proxy, and often outdated datasets. This significantly limits the potential of LCA to give reliable support to decision making when it comes to discriminating products based on their environmental footprints. Achieving specificity at a large scale in LCA requires fundamentally changing the way emission data is collected, stored, and exchanged.

The objective of this research project is therefore to define and develop a framework that facilitates the mass deployment of semi-automated, supply chain-specific cradle-to-gate carbon footprint calculations, without requiring the exchange of sensitive proprietary data. Key features of the framework include decentralizing the inventory collection and impact assessment, so that production functions remain with the respective companies. More specifically, they remain in an automated calculator that is linked to a database with carbon footprints reported by other actors, allowing them to instantly capture changes in suppliers' footprint disclosures. While this would substantially reduce the effort of an attributional carbon footprint assessment, the solutions and features proposed in the framework present new challenges, which are identified and discussed in this project in terms of how they can be addressed in practice and their implications.

This research project offers important insight into how we can get to a point where every product and service has its unique carbon footprint transparently displayed, the same way it has a unique monetary cost. Access to carbon footprints with more specificity would not only help consumers to reduce their consumption-based impacts, but it could also push companies to take accountability for, and reduce, their indirect impacts. The framework and overall findings, however, are applicable for any impact category, not just that of climate change.

Resources & Materials

Environmental sustainability and climate resilient supply chains: the case of advanced biofuel production in the EU

Monday, 3rd July - 09:00: Resources & Materials (B0.31 KOG)

Lars Wietschel [1], ***Martin Bruckler*** [2], ***Lukas Messmann*** [3], ***Selina Sartor*** [4], ***Andrea Thorenz*** [2], ***Axel Tuma*** [5]

1. University of Augsburg, 2. Resource Lab / Center for Climate Resilience – Augsburg University, Germany, 3. Resource Lab – Augsburg University, Germany, 4. University of Augsburg, Resource Lab / Centre for Climate Resilience, 5. Chair for Production & Supply Chain Management – Augsburg University, Germany

Second-generation bioethanol promises environmental and societal advantages, both vis-à-vis petrol and first-generation bioethanol. However, biomass supply chains are characterized by several vulnerabilities; particularly agricultural feedstock supply is subject to significant annual fluctuations. Even in the optimistic 1.5°C global warming scenario, temperature extremes, heavy precipitation, and droughts will occur with higher frequency and intensity. Precautionary measures that increase the resilience of feedstock supply to disruptions should be considered as early as in the strategic stage. However, resilience measures, such as large feedstock storages or alternative supply regions, alter physical material flows. Changing material flows can imply higher economic and environmental impacts compared to the most efficient solution. Additionally, strong disruptive events can shift the valuation of business objectives: the (sub-) goal of minimizing environmental impacts might fade into background in order to ensure the economic survival. Thus, how resilience measures affect the environmental sustainability of advanced biofuel supply chains depends on several countervailing factors.

In this work, we employ a two-stage stochastic linear programming approach to consider resilience explicitly in strategic network decision-making for bioethanol production in the EU. Resilience is considered in form of satisfying objectives (e.g., minimum bioethanol production per refinery also in case of supply disruption). By relaxing the satisfying objectives for resilience, we explore how the performance in terms of resilience and sustainability relate to one another. In detail, first-stage decisions in the model include '*here-and-now*' decisions (e.g., locations and capacities of biorefineries and storages), while second-stage decisions (e.g., feedstock sourcing and bioethanol distribution), are taken recurringly with each realization of the stochastic feedstock supply. The model is parameterized by economic as well as LCA-based environmental data for 21 midpoints and endpoints (ReCiPe 2016). The stochasticity in the regional feedstock supply is represented by regionally correlated distribution functions, which are retrieved from trend-adjusted historic feedstock supply data on NUTS-1 level. The decisions that are taken to account for supply disruptions comprise strategic, absorptive measures (e.g., construction of storages to level out fluctuations) and operative, adaptive measures (e.g., diversification of supply regions, restructuring transportation links) and vary depending on the respective objective. Preliminary results show that a strong focus on resilience compromises the environmental and economic performance of the production network. By relaxing the satisfying objectives for resilience stepwise, we find interesting trade-off solutions that are simultaneously resilient, while maintaining a good level of environmental and economic efficiency. Lastly, we quantify the improvement in resilience from these decisions by applying state-of-the-art resilience metrics and discuss how the resilience metrics and the various environmental and economic objective values interrelate. This work shows the benefit of considering climate change-induced uncertainties in strategic supply chain planning.

In particular, the combined application of LCA-based parameters and resilience metrics allows for assessing resilience-oriented decisions as well as trade-offs between resilience and sustainability − both of which is hitherto underrepresented in current literature on biomass supply chain planning and related fields at the intersection between optimization, resilience, and sustainability.

Lignocellulose Biomass as a Chemical Feedstock: Regional Availability and Environmental Impacts till 2050

Monday, 3rd July - 09:15: Resources & Materials (B0.31 KOG)

Jing Huo [1], ***Zhanyun Wang*** [2], ***Pekka Lauri*** [3], ***Gonzalo Guillén-Gosálbez*** [4], ***Stefanie Hellweg*** [1]

1. *Institute of Environmental Engineering, ETH Zurich,* ***2.*** *Empa-Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory,* ***3.*** *International Institute for Applied Systems Analysis,* ***4.*** *Institute of Chemical and Bioengineering, ETH Zurich*

As the largest fossil fuel consumer and the third largest industrial greenhouse gas (GHG) emitter, the global chemical industry must shift away from fossil towards renewable feedstocks in order to reach net-zero GHG emissions by 2050. Lignocellulose biomass, widely available in wood and agricultural residues, is the most abundant form of inedible biomass globally, but with large regional variability. In bio-refineries, they can be converted into simpler molecules such as glucose and xylose, major building blocks for top ten bio-chemicals envisioned by the United States Department of Energy.

In this study, we estimate the regional availability of lignocellulose biomass as a chemical feedstock in 2050 under two Representative Concentration Pathway (RCP) scenarios using the Global Biosphere Management Model (GLOBIOM): the no-carbon-mitigation RCPref scenario and the net-zero-by-2050 RCP1.9 scenario. To minimize potential competition with land use for food production and existing forest-based industries, we focus only on the harvest and process residues of agriculture (staw, husks, etc.) and forest (logging residues, sawn dust, etc). We further conduct cradle-to-gate life cycle assessment to analyze the regionalized environmental impacts of various agricultural and forestry residues as chemical feedstock. The assessed impacts include climate changes impacts, water scarcity, and land use-related biodiversity loss.

Our preliminary results indicate that the global available potential of lignocellulose biomass from lignocellulose residues in 2050 is around 3.4–5.3 gigatonnes (Gt) of dry mass. When assuming theoretical maximum conversion yield, this is enough to produce 1.5–2.3 Gt of glucose and 1.0–1.5 Gt of xylose. About half of the global agricultural residue biomass available potential is located in India, China, the United States and Brazil. Additionally, the European Union, the United States, China, and Russia have the highest potential for forest residue biomass, representing nearly 45% of the global availability.

This regionalized assessment of the availability and environmental impacts is crucial for identifying suitable regions with the lowest environmental impacts from the production of bio-based chemicals with lignocellulose biomass feedstock. This information can be used to optimize the choice of lignocellulose biomass feedstock and its supply chain, and to minimize the environmental footprints of the global chemical industry.

Can industrial agglomeration increase the wood resource efficiency?

Monday, 3rd July - 09:30: Resources & Materials (B0.31 KOG)

Chenlu Tao [1]***, Chang Yu*** [2]

***1.** North China Electric Power University, **2.** Beijing Forestry University*

Wood is the only biodegradable, renewable, and recyclable material among the four major raw materials (i.e., wood, steel, cement, and plastics). The use of wood resources would replace high-energy-consumption materials, which can achieve the goal of sustainable resource utilization and play an essential role in protecting the environment and mitigating climate change. China is the major timber importer and wood processing country with a complete upstream and downstream industrial chain. The features of industrial agglomeration are important to promote the wood processing industry. Taking the wood-based panel cluster in Linyi, Shandong, as an example, the regional annual production capacity has reached more than 30 million tons, a leading position throughout the world. Therefore, China's wood resource efficiency has a crucial influence on the global wood utilization rate.

This study aims to explore the impact of industrial agglomeration on wood resource efficiency and evaluate the possibility of improving efficiency by building or expanding wood processing clusters. We employed semi-parametric estimation to calculate the total factor productivity (TFP) of Chinese wood processing enterprises and analyzed the TFP's spatial-temporal evolution. Furthermore, we discussed the relationship between spatial agglomeration and China's wood resource efficiency based on the econometric regression model and heterogeneity analysis. The results show that the average TFP of Chinese wood processing enterprises increased rapidly from 1998 to 2007, which increased by nearly 50% in ten years. But the continuity for productivity growth is insufficient after 2010.

We also found that the spatial agglomeration of China's wood processing industry has a significant positive impact on TFP through three aspects: "labor", "goods" and "innovation", which proves it is feasible to improve the productivity of enterprises and enhance the utilization efficiency of wood resources by rational utilization of agglomeration effect. In terms of enterprise ownership heterogeneity, the spatial agglomeration of state-owned wood processing enterprises has a significantly greater positive impact on TFP than private enterprises. It is strong evidence of the absolute advantage of state-owned capital in the overall and optimal allocation of resources. In the aspect of land price, it indeed brings negative externalities to the agglomeration effect of the wood processing industry, and high land price offsets the economic externalities brought by agglomeration. As for the heterogeneity of natural forests, China has banned the cutting of natural forests since 1998, and commercial cutting of natural forests has been completely stopped since 2020. Therefore, the promotion effect of agglomeration on productivity has little to do with different natural forest stock in areas. By contrast, planted forests in China provide raw materials like logs for enterprises. In areas with larger forest plantations, agglomeration can give full play to the advantages of economic externalities and promote productivity. It demonstrates that improving agglomeration in regions with comparative advantages in resources can bring greater impetus to productivity.

Recently, the wood processing industry has been gradually emerging in developing countries like Southeast Asia. China's wood processing industry can provide advanced experience and lessons for other countries regarding industrial cluster allocation and development models.

Bulk Materials Supply in a Zero-Emission Future with Uncertain Technology Adoption

Monday, 3rd July - 09:45: Resources & Materials (B0.31 KOG)

Takuma Watari [1], ***Lukas Gast*** [2], ***André Serrenho*** [2]

1. National Institute for Environmental Studies, 2. University of Cambridge

Global steel and cement production has more than doubled over the past two decades and now accounts for about 15% of global CO_2 emissions. Clearly, how we produce and use bulk materials needs to be transformed to achieve a zero-emission future, an absolute requirement for a stable climate. But how is it possible to decarbonise bulk materials production within a limited timeframe? Decarbonisation scenarios usually find their solutions in the rapid deployment of supply-side technologies, including carbon capture and hydrogen technologies. However, the deployment of these technologies is highly uncertain in the face of technical, economic, and social challenges.

This study explores bulk materials supply in a zero-emission future with uncertain technology deployment using a stochastic optimisation model. The model explicitly considers uncertainties in the adoption of carbon capture and non-emitting electricity (i.e. green hydrogen) and calculates global materials supply in line with a 1.5 °C carbon budget. The results show that staying within the carbon budget with limited deployment of carbon capture and non-emitting electricity technologies would lead to significant scarcity and uncertainty in the supply of bulk materials. Despite growth in hydrogen-based and scrap-based steelmaking, total steel supply could fall to 65-75% (interquartile range) of current levels by 2050 under the 1.5 °C carbon budget. Cement supply could be even scarcer and more uncertain due to limited mitigation options, remaining at 30-65% of current levels by 2050. These results suggest that bulk material suppliers and users should prepare well for the scarcity and uncertainty of zero-emission compatible bulk materials, rather than simply waiting for technological innovation on the supply side.

Critical Raw Material demand modeling for substitutable materials and future technologies

Monday, 3rd July - 10:00: Resources & Materials (B0.31 KOG)

Christoph Helbig [1]

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Global material stocks for metals and minerals are rising because of overall growth in affluence, population growth in some world regions, and growth in market penetration for various modern and future technologies. The growth of metal stocks and a widespread lack of circularity for specialty metals and Critical Raw Materials (CRMs) leads to a high demand for primary materials mining and processing. This primary production of metals leads to significant environmental impacts, such as 8% of the global GHG emissions, deforestation and other land transformations, and water consumption in arid regions.

Moreover, concerns for future mineral resource availability are widespread, particularly CRMs. It is not necessarily the global geological availability of metals and minerals, expressed in reserves and resources, that is problematic. More so is the question of whether mining and refining capacities can keep up with the rapid demand growth of future technologies. And if these capacities are considered sufficient, material access may still be limited due to a high market concentration, energy availability, trade barriers, or growing political tensions. Therefore, to estimate future environmental impacts and the need for capacity expansion in mining and refining, demand modeling over decades is crucial, even for specialty metals produced in smaller quantities as by-products. However, many metals are mutually substitutable and can fulfill similar functions. Substitution can also happen on a component or technology level. Growing markets and future technologies are particularly challenging to model decades into the future.

Current practices for modeling the future demand in Industrial Ecology primarily work with ex-ante-defined technology-adoption scenarios. One example is the modeling of battery material flows, where future battery market development is uncertain regarding battery market growth rates and future battery technologies. Some authors open a range of possible futures by modeling two scenarios for future battery technologies: one lithium nickel-manganese-cobalt oxide (NMC) scenario and one lithium-iron-phosphate (LFP) scenario. They obtain boundaries for possible futures and may conclude that one scenario seems unfeasible given reserve volumes or production capacities. Similar examples exist for wind turbines, permanent magnets, solar cells, or the hydrogen economy.

I show that such approaches for future demand modeling can be improved significantly by including feedback loops with information on primary production capacities, metallurgical and process engineering modeling, material or technology level substitution, and end-of-life recycling. The challenges for applying these feedback loops into demand modeling comprise knowledge gaps on the cost structures of CRM producers, detailed application shares and possible substitution rates, and future end-of-life waste collection rates.

Improvements in the demand modeling for substitutable materials and future technologies can be used to calculate more realistic stock-and-flow dynamics scenarios in dynamic Material Flow Analysis. Further, the models can refine criticality assessments for raw materials on a national or corporate level. Lastly, the results of improved demand scenarios in Industrial Ecology models will help estimate the environmental impacts during the global technological and societal transitions.

Assessing the potential supply risk mitigation for strategic raw materials in the EU: Evaluation of the benchmarks from the Critical Raw Materials Act

Monday, 3rd July - 10:15: Resources & Materials (B0.31 KOG)

Jair SANTILLAN SALDIVAR [1], ***Anish KOYAMPARAMBATH*** [2], ***Guido SONNEMANN*** [2], ***Daniel MONFORT CLIMENT*** [1]

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Methods to assess raw material criticality have become key tools to support the development of multiple countries and regions around the globe. Specifically, the European Union (EU) has been regularly providing lists of critical raw materials to pilot strategic sectors in the EU economy. The latest iteration of the criticality assessments introduces the Critical Raw Materials Act (CRM Act), which establishes benchmarks and potential actions in order to mitigate the criticality of the strategic raw materials by 2030. Our contribution aims to provide a prospective assessment of the impact of these objectives in the supply risk of critical raw materials through an integration of the GeoPolRisk method and a linear programming model.

The GeoPolRisk method is used in criticality assessments and life cycle assessments to estimate the supply risk of a resource from the perspective of an economic agent; it considers global production and trade information to calculate characterization factors tailored to different sourcing scenarios and measures potential supply risk in monetary units. In this contribution, we apply a linear programming model based on the GeoPolRisk method to estimate the potential supply risk mitigation expected from the completion of the benchmarks established in the CRM Act with focus on the list of strategic raw materials. We built the linear programming model using "geopolrisk-py", an open-source python based library that operationalizes the GeoPolRisk method.

Results show potential improvements to the supply risk profile for multiple resources due to expected reduced dependency from producers located in areas with high risk of supply disruption. We also estimate the requirements in terms of domestic production and recycling to achieve the benchmarks established for 2030. Among the analyzed strategies, recycling can be suggested as the most adequate option in terms of risk mitigation; however, the results should complement other type of assessment in order to inform decision-making processes in a more comprehensive way: environmental impacts, technical feasibility, social impacts and resource economics.

The analysis of the list of strategic raw materials for the EU is limited by the amount of public information required for the assessment; specifically for the case of rare earth elements, the application could improve if more detailed production and trade data becomes available. Moreover, application of the method at intermediate points in the supply chain could further reveal bottlenecks associated to the transformative industry. Results obtained with the GeoPolRisk method should be used in parallel to other methods focused on socioeconomic and environmental aspects of resource management to inform government agencies on the feasibility of the proposed strategies.

EVs and batteries

Reverse logistics of critical elements derived from electric vehicle lithium-ion batteries

Monday, 3rd July - 09:00: EVs and batteries (C1.31 KOG)

Abhimanyu Raj Shekhar [1]***, Miriam Stevens*** [1]***, Shweta Singh*** [1]

1. *Purdue University*

The recent advancements toward national electrification of the US have led to the rapid manufacturing of massive quantities of electric vehicles (EVs) that utilize high amounts of lithium-ion batteries (LiBs). However, such development poses the risk of accelerated exhaustion of primary critical metals and generation of excessive battery waste. Critical metals like cobalt (Co), nickel (Ni), and manganese (Mn) serve to be excellent precursors in the battery manufacturing industry as they can be recycled indefinitely without losing their physical properties or chemical characteristics. The circularity of these critical metals in an economy can be advanced by analyzing potential reverse logistics scenarios based on the construction of spatial network of cost-optimized battery recycling facilities. In this research, we demonstrate the development of a regional structure of battery recycling facilities and spent battery collection centers in the US under deep future uncertainties associated with the variation in market share of LiB chemistry composition and the adaptive changes in battery recycling technology. Using RELOG: Reverse Logistics Optimization, a simulation of battery collection and recovery was created over a 30-year timeline spanning till 2050, with a LiB chemistry composition of 62% NCA and 38% NMC reflecting the current market share of cathode chemistries in the EV sector. Simulating three specific recycling technology cases, viz. pyrometallurgical, hydrometallurgical, and direct, the preliminary result provided the spatial distribution of collection centers, disassembly plants, and battery recycling facilities, along with the cost and emission data for each case. Primarily, the development of direct recycling facilities across the nation came out to be the most cost-optimal solution when including recovered material resale value as a revenue source. A comparative assessment is anticipated to be carried out for this baseline scenario with two extreme future scenarios, one where the market share comprises 12% NCA, 38% NMC, and 50% LFP; and the other being 12% NCA and 88% LFP, in compliance with the future trend towards reliance on LFP-based batteries.

Towards a sustainable battery manufacturing modelling platform

Monday, 3rd July - 09:15: EVs and batteries (C1.31 KOG)

Daniel Perez Clos [1], ***Joris Baars*** [2], ***Felipe Cerdas*** [3], ***Sabrina Zellmer*** [2], ***Anders Hammer Strømman*** [1], ***Christoph Herrmann*** [3]

1. *NTNU,* ***2.*** *Fraunhofer IST,* ***3.*** *Technische Universität Braunschweig*

Lithium-ion batteries are essential for consumer electronics, stationary storage systems and especially electromobility but are expensive and are linked to substantial environmental footprint. To improve the environmental sustainability of batteries, innovative battery design and production processes across the entire value chain are currently under development. Life cycle assessment (LCA) and cost assessments can help support such developments by providing direct feedback and optimise technical decisions from a sustainability point of view. Lithium-ion batteries and their production however is complex and characterised by many technical parameters that influence the sustainability. Current sustainability assessment models lack the engineering refinement to capture these parameters and simulate battery manufacturing processes that are useful for technical decisions making. Therefore, to support the ongoing and growing battery technology developments in research and industry, new sustainability assessment to capture such technical details are needed.

In this work, a new modelling platform for environmental and techno-economic assessments of batteries is presented. The platform implements detailed product and process models used to simulate the manufacturing energy and material flows, and links them to LCA and cost assessment models. By modelling battery and machine-specific parameters, complex and extensive analysis of novel battery technologies can be explored. Furthermore, due to its flexible and modular structure, models of new battery technologies, machines and process routes can be easily integrated in the framework. In this work, the overall logic and design of the platform, the different models and their linkages are introduced. The capabilities of the platform are illustrated by means of a case study of a conventional lithium-ion cell production route versus a novel semi-solid electrode cell production concept. This work concludes by highlighting how such a modelling platform can enhance the relevance and application sustainability assessments in engineering.

ESG reporting for Australian battery materials: comparing data requirements and quality for voluntary and regulatory mechanisms

Monday, 3rd July - 09:30: EVs and batteries (C1.31 KOG)

Rusty Langdon [1]***, Fiona Berry*** [1]***, Stephen Northey*** [1]***, Damien Giurco*** [1]***, Wen Li*** [2]

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Governing bodies, investors, and researchers alike have highlighted the importance of accurate, transparent, and comparable data in environmental, social and governance (ESG) reporting. However, the level of quality, consistency, and comparability of ESG reports and management practices is an ongoing issue. As the world transitions to renewable energy and storage technologies, Australian battery material producers are under increased pressure to produce responsibly and disclose credible ESG information. In the absence of a common or mandatory Australian ESG reporting framework, producers are forced to grapple with reporting to both Australian regulatory mechanisms and a large swath of voluntary ESG reporting mechanisms, to fulfil the ESG reporting and management requirements of a range of global stakeholders. Variations in scope, transparency, and verification of reported information creates challenges in terms of interpreting and monitoring broader industry shifts towards sustainable practices and in identifying good and bad actors.

Our research assesses the current level of standardisation of data requirements, methodologies, scopes, and level of transparency across voluntary and regulatory ESG reporting and management mechanisms. This is within the bounds of mechanisms relevant for Australian mining and processing companies that produce common battery materials and their by-products, such as lithium, nickel, cobalt, vanadium, and graphite. The voluntary ESG reporting mechanisms we have considered for this study include non-assured standards such as the Responsible Mining Index (RMI), the Global Reporting Initiative (GRI), the OECD Due Diligence Guidance on Stakeholder Engagement for the Extractives Sector (OECD), and the Carbon Disclosure Project (CDP); assured standards such as Towards Sustainable Mining (TSM), and the Dow Jones Sustainability Index (DJSI); and certifications such as the Certification of Raw Minerals (CERA), and the Initiative for Responsible Mining Assurance (IRMA). The regulatory reporting mechanisms we have considered include the National Greenhouse and Energy Reporting Act 2007 (NGER Act), the National Environment Protection (National Pollutant Inventory) Measure (NPI), and also environmental impact assessment and management processes under the Environmental Protection & Biodiversity Conservation Act 1999 (EPBC Act). The results of our research highlight the lack of standardisation of data, methodologies, transparency, and verification across ESG indicators common to a range of voluntary and regulatory reporting and management mechanisms. We discuss the challenges for the Australian battery materials sector reporting to an undefined set of voluntary and regulatory mechanisms and highlight best practice examples of reporting guidance that may avoid data quality and comparability issues moving forward.

Evaluating the implication of cobalt free electric vehicle batteries on the potential for lifetime extension through repurposing in electricity markets

Monday, 3rd July - 09:45: EVs and batteries (C1.31 KOG)

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The adoption of electric vehicles is expected to grow drastically in the coming years and while much effort is invested in the design and technology side of battery manufacturing, less attention is drawn for their end-of-life fates. Currently, there is significant interest in a technology shift to cobalt free cathodes in Li-ion batteries due to a desire to reduce exposure to potential interruption of this critical raw material in their supply chain. but this shift is also likely to have consequences for their end-of-life decisions as well. Thus, further end-of-life standardization and qualification assessment toward recycling and repurposing are required for different battery chemistries in electric vehicles.

This work aims to quantify the second use feasibility of Cobalt free cathode Li-ion chemistries i.e., LFPs and the current dominant technology NMCs, in a comparative assessment. This analysis takes their second-life application for energy arbitrage trading in the electricity markets. This evaluation is specifically focused on the economic advantages of repurposing the two chemistries, with a sensitivity analysis to the market potential, refurbishing costs, size of the system, and battery duration. Results of this analysis will show how various cathode chemistries promise different second lifetime and business opportunities which make such repurposing feasible. Further, the repurposing practicality can be used as an indicator for their sustainability assessment.

Can second-use of EV batteries in Energy Storage Systems reduce demand for critical raw materials in Europe more than recycling?

Monday, 3rd July - 10:00: EVs and batteries (C1.31 KOG)

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Electric Vehicles (EVs) are becoming increasingly popular in Europe due to their perceived environmental friendliness and cost-effectiveness. However, one of the most critical challenges remains to find an efficient way to use EV batteries after they reach their end-of-life (EOL). One solution is using EV batteries in a secondary life as a stationary Battery Energy Storage System (BESS). BESS can help increase battery lifespan and store energy from renewable sources (RS) such as wind and solar. Additionally, the supply of Critical Raw Materials (CRMs) is an imminent challenge for Europe. Second-life to EV batteries has the potential to offset the use of CRMs in new battery manufacturing for BESS. However, using EV batteries in BESS reduces the available quantity of recycled CRM for new EV battery production leading to an increase in primary CRM demand. Therefore, there is a need to assess the dynamics of second-life EV batteries supporting BESS and its effects on CRM demand in Europe.

The study explores to what degree the capacity of batteries from EVs reaching their EOL in Europe may be sufficient to support BESS by 2050 and the subsequent effects on CRM demand. The study is divided into multiple parts. First, a dynamic stock model (DSM) is employed to estimate the number of battery EVs (BEVs) and Plug-in hybrid EVs (PHEVs) in Europe, reaching EOL for each age cohort from 2018 to 2050 across each EU member state. Subsequently, a dynamic battery stock model (DBSM) is developed to assess the stock, degradation of different battery types, and capacity under different rates of recovery for second use from the EVs reaching EOL. This available capacity is compared to the demand for new batteries required in BESS and EVs, which allows for estimating the offset demand in primary CRMs. In scenarios, the effect of different BESS demands, recovery rates for reuse of EV batteries, and recycling efficiency of batteries are explored. The strength of this study resides in the detailed dynamic modeling of EV batteries for use in BESS in Europe, considering spatial and time variabilities. The results show the share of the overall RS electricity generation that second-life EV batteries in BESS can support by 2050. This study also indicates a possible tension between BESS and EV sectors without supportive actions in increasing CRM availability for the EV sector and the importance of CRM recycling efficiency.

Buildings & Infrastructure 1

SDG scoring at building-level for Hong Kong using Big Data and Machine Learning approach

Monday, 3rd July - 09:00: Buildings & Infrastructure 1 (B0.41 KOG)

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Existing neighborhood sustainability assessment (NSA) tools use a traditional triple-bottom-line methodology that places an imbalanced and non-spatial focus on sustainability dimensions. This results in a lack of actionable insights for stakeholders, government, urban planners and the general public to make decisions based on their needs and priorities. Presently, spatial inequity of infrastructure access is observed at building-level, neighborhood level and district level. However, the spatial inequity associated with the Sustainable Development Goals (SDGs) and, in particular, their respective indicators are not well understood at the neighborhood scale to inform urban design.

To overcome this problem, this study focuses on developing an algorithm purely based on machine learning and geospatial models to compute and assess the sustainability scorings at the building level. The algorithm utilizes automated data scrapping from online open data portals and other resources, which are cleaned and preprocessed in the next step. The data points include facilities, census and statistics data at building level, services and other resources. The resultant list of individual buildings is mapped, with all 17 sustainable development goals, which breaks down to 232 unique target indicators. We select those indicators that are pertinent to urban systems for the calculation of the scores for each SDG. An aggregated final SDG score can be used to compare buildings in a neighborhood in terms of their overall score that takes into account the performance for each SDG.

The methodology of this paper is focused on the entirety of Hong Kong. However, this methodology can also be applied to other cities and/or countries, given that data points are available as model input. The developed methodology aims to address individual SDG status at the building level, which can also be grained at the neighborhood or district level. This will help to understand how sustainable individual buildings are and provide guidelines to access neighborhood sustainability. The resultant scoring will help to attain overall higher SDG scoring for all buildings by understanding the hotspots for improvement. The individual scoring will help to analyze the current sustainability aspect of buildings and will help in the decision-making of suitable actions to enhance the overall SDG of the area. This will act as a guideline for policy makers and urban planners to understand where and how to improve overall sustainability of a neighborhood.

Sensors instead of wall insulation? An evaluation of advanced building control as retrofit option

Monday, 3rd July - 09:15: Buildings & Infrastructure 1 (B0.41 KOG)

Hannes Gauch [1], ***Scott Jeen*** [1], ***Jack Lynch*** [1], ***André Serrenho*** [1]

1. *University of Cambridge*

The UK has one of the oldest and least energy efficient housing stocks in Europe. 25 million homes will need to be upgraded before 2050 to reach net-zero emissions [1]. Until now, retrofit modelling and guidelines mostly focus on the upgrade of the building fabric (draft proofing, insulation, windows), of HVAC systems (heat pumps, mechanical ventilation), and on on-site generation (solar panels). Many of these interventions are expensive for homeowners and, applied on the necessary scale, pose challenges to supply chains, availability of labour and expertise, and sustainability of materials. We therefore ask the question: Is it possible to ease the retrofit challenge by making better use of our buildings?

The behaviour of occupants—such as their interaction with heating systems, windows, and other equipment—is a governing factor for building energy consumption [2]. Optimising the use of a building using sensor data and control algorithms can therefore be an effective way to reduce emissions and energy consumption from buildings [3]. Recently, advanced building control using reinforcement learning (RL) is being explored for its energy and emissions saving potential. By finding control strategies for using the grid electricity; heating, cooling, and ventilating the building; charging batteries; and heating water; savings in the order of 10-30% have been achieved [4], [5]. These findings have, however, not been generalised yet to the ubiquitous small residential buildings in their various stages of retrofit.

Considering the most common dwelling type in the UK, the semi-detached house, we evaluate the benefit of advanced building control at various combinations of fabric and energy system upgrades. To this end, we use our software package CUBES (Cambridge Universal Building Energy Simulator) which creates building models in EnergyPlus and sets up the interface with RL agents programmed in Python. Our results will reveal which fabric-energy system combinations benefit most from advanced control, and if implementing advanced building control could be seen as an effective, low-cost retrofit option.

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Identifying the geographical potential of rooftop systems: Space competition and synergy

Monday, 3rd July - 09:30: Buildings & Infrastructure 1 (B0.41 KOG)

Mike Slootweg [1]***, Mingming Hu*** [2]***, Solmaria Halleck Vega*** [3]***, Maarten van 't Zelfde*** [2]***, Eveline van Leeuwen*** [3]***, Arnold Tukker*** [2]

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Urban areas face severe challenges in mitigating and adapting to climate change within limited space. One solution is to develop multifunctional rooftop systems, which use underexploited urban rooftop spaces. Two main options have been to add greenery by installing extensive green roofs (EGRs) or to generate renewable energy by installing photovoltaic panels (PVs). Recently, combining the two systems on one rooftop (EGR-PV) to harvest both benefits has gained attention. Not every rooftop is suitable for such installations, which makes it difficult to estimate the scale of space a city can expect from rooftops to add greenery, renewable energy, or both.

This study presents a geographical potential model using building parameters, a building stock layer, and LiDAR data to simultaneously identify the potential for installing EGRs, PVs, and EGR-PVs on rooftops, highlighting the competition and synergy between EGRs and PVs at the building level. As an empirical illustration to support future multifunctional urban rooftop space planning, Amsterdam was used as a case study. The results show that 47 % of rooftops are suitable for EGRs, which could expand the current greenery space by 6 %, and 55 % are suitable for PVs which could sufficiently provide electricity to households by 2030. Moreover, competition exists for 3.2 %, whereas synergy exists for 42 % of the existing rooftops.

Scaling building-level heat demand modelling to provide high-resolution insights in support of climate change mitigation and circularity policies across the European Union

Monday, 3rd July - 09:45: Buildings & Infrastructure 1 (B0.41 KOG)

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***1.** Technical University Berlin, **2.** City of Zurich, **3.** University of Edinburgh, **4.** Paris-Saclay Normal School, **5.** New York University Abu Dhabi, **6.** Mercator Research Institute on Global Commons and Climate Change (MCC), Berlin, **7.** ETH Zurich, **8.** Hertie School, **9.** Potsdam Institute for Climate Impact Research (PIK)*

The European Union (EU) and its member states are aiming to strongly increase renovation rates of the EU building stock to reach the targets from the Paris agreement. Large amounts of funding are being unlocked but it is unclear how to best allocate investments due to the lack of comprehensive and granular information about the thermal performance of the building stock.

Here, we propose a modeling approach that estimates the energy demand for space heating and simulates deep retrofits for every single residential building of five countries representative for western EU countries across relevant climate zones (Sweden, France, Netherlands, Switzerland and Spain), and with the potential to be scaled to all the EU at a latter stage. This enables to identify hotspots of building energy reduction potential down to the communal level and simulate various alternative renovation strategies.

Our approach builds on a standard physics-based engineering model (ISO 52016) that we can scale to more than 70 million buildings by combining deterministic localized building stock and climate information with probabilistic thermal performance information from archetype data. We use the open-access database EUBUCCO developed by the authors to provide information on location, dimensions, age and usage of each individual building. We match each building to thermal performance information from the TABULA dataset and use Monte Carlo simulations to reflect the uncertainty in parameter values.

In the talk, I will present the methodology and provide insights from our validation work in which we compare our model inputs and outputs to large scale energy performance certificate datasets in France and Spain. Those datasets contain building-level yearly energy consumption for space (and hot water) heating and a few thermal performance parameters such as U-values. Thus, they enable to study existing patterns across building types and regions from measured data, and investigate when a model based on simplified inputs can or cannot reproduce those patterns.

I will also discuss the results for our scenario work. We compare for example a uniform retrofit strategy with a targeted one based on the identified hotspots and aim to understand if and how such a scenario may outperform a uniform scenario. This may then support an effective prioritization of most effective retrofit investments on a country as well as on a communal level.

The approach was initially built for a climate change mitigation use case but is highly relevant for broader industrial ecology applications. Indeed, it enables to build scenarios of retrofit where it is possible to investigate the impact of retrofitting individual building elements and the relevant material implications. I will exemplify how such analyses could be carried out in the context of circularity strategies. All the source code of the project will be made openly accessible in the future.

Estimating the construction material stocks in developing countries: Case study of Lahore, Pakistan

Monday, 3rd July - 10:00: Buildings & Infrastructure 1 (B0.41 KOG)

Komal Habib [1]

1. University of Waterloo

Growing global population and expansion in urban areas is raising concerns regarding increasing demand for limited resources. Among all the materials consumed, construction materials are responsible for the greatest share of material use in cities. This research is aimed at measuring the amount of construction materials embedded in the residential buildings in the mega city of Lahore, Pakistan. Lahore is the economic and industrial hub of Pakistan with a population of more than 11 million as of 2017, and an average annual population growth rate of 3 % from 1998 to 2017. Material stock accounting is a tool that is used in this study to estimate the mass of construction materials used in Lahore city from 2017 to 2050. This research uses a combination of data collection methods (top-down, bottom-up, demand-driven, and remote sensing). The preliminary results show that in 2017, almost 419 Mt of construction material was used, resulting in 37.64 t per capita. The most dominant construction material has been brick, followed by sand and aggregates. It is estimated that by 2050, 692 Mt of construction material stock will be added to the residential buildings sector of Lahore. Detailed results will be included in the final paper.

Achieving net-zero raw material consumption for future urban built environments

Monday, 3rd July - 10:15: Buildings & Infrastructure 1 (B0.41 KOG)

Yupeng Liu [1]***, Kangning Huang*** [2]***, Wei-Qiang Chen*** [1]***, Karen Seto*** [3]

1. *Institute of urban environment, CAS,* ***2.*** *New York University Shanghai,* ***3.*** *Yale University*

The anticipated population growth and global urbanization over the next several decades will create a vast demand for constructing new housing, commercial buildings and accompanying infrastructure. Such huge size of construction, especially in developing worlds, it is expected to release 226 gigatonnes (Gt) of greenhouse gas emissions (GHGs) by 2050 —— more than 2 times the amount used in existing infrastructure and claiming ~28% of a remaining carbon budget. The fundamental solutions are to reduce consumption of mineral-based construction materials and/or replace them by bio-based materials (e.g., wood). Such strategies could be named as 'material-saving wedges' according to the substantial synergy effect of material use reduction and carbon emission mitigation. For example, demand-side mitigation by avoiding oversize dwelling and superfluous floor space for equipment (e.g., heating, cooling, IT), sharing common spaces and related approaches, is the most fundamental wedge to reduce the size of new construction and related material use. Besides, the Intergovernmental Panel on Climate Change (IPCC) assessment report identifies not only the size of urban building clusters but also their spatial distribution, also known as urban form, often matter for material consumption. For example, heading to a 'flat' and sprawl form results in the spreading of urban buildings such as houses and shopping malls near a city and potentially increased material consumption in the transportation infrastructures. However, we still have little understanding of how future building growth and urban form changes would manifest material use. Our primary goals in this study are to develop possible scenarios of future building growth and urban form and to estimate potential material use among different global and urban futures.

We developed a dynamic and spatially explicit model to predict volumetric change of global building environment through 2050. We found global buildings would enlarge to 1.5 times of current size by 2050 and grow faster in volume than in lateral. Most of the developed and developing regions would experience a 'net' increase in building stock except for Europe. The largest amount of building expansion could come from Asia and the fastest speed of building expansion could occur in Africa. At a region or single city level, we found five possible changing typologies based on the characteristics of building growth or shrinking, which are termed as upward and outward, mature upward, stabilized, mature flatted, and shrinking.

We further estimated material demand for future construction and renovation. We found the man-made world would be 'rebuilt' once in next 30 years and consume additional one-third of in-use anthropogenic mass. Therefore, we designed five material-saving wedges to mitigate future demand, including reduce demand (RD), life extension (LE), material diet (MD), reuse & recycle (RR), and prefabricated building (PB). We found a net-zero raw material consumption could be achieved by combined 5 material-saving wedges. Among them, the MD wedge would fundamentally change structure of future material demands——leading to a growing demand on environment-friendly materials (e.g., wood) but significantly reducing demands on carbon-intensive and heavy-weight materials (e.g., steel and concrete).

Plastics: impacts

The environmental potential of plastic recycling from a system perspective

Monday, 3rd July - 09:00: Plastics: impacts (C0.06 KOG)

Magdalena Klotz [1]***, Melanie Haupt*** [2]***, Christopher Oberschelp*** [3]***, Cecilia Salah*** [3]***, Luc Subal*** [3]***, Stefanie Hellweg*** [1]

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Plastics are an integral part of our modern life, whereby, on the downside, they are projected to use up 15% of the total greenhouse gas emissions budget for keeping global warming below 1.5°C by 2050. Recycling can lower CO_2 emissions related to plastics production and waste incineration. Hereby, the specific composition of different plastic products affects both recyclability and utilization options for recycled plastics. Therefore, a high-resolution material flow model is key for determining the recycling potential. We developed such a model (11 plastic types, 69 product groups) for assessing to which extent mechanical recycling may be increased in the future and how chemical recycling could complement it. The related environmental benefits were quantified via a life cycle assessment. The study was performed for Switzerland, but is in many aspects representative also for the wider European context. The mechanical recycling rate, calculated as ratio of utilizable secondary material to waste, that can be achieved via improved product design, increased waste collection and a more specific sorting amounts to only 30% on a system level. This maximum mechanical recycling could lower the plastics carbon footprint by one quarter compared to energy recovery in waste-to-energy plants. Additionally, chemical recycling of plastics that cannot be mechanically recycled, but are separable from other materials, could reduce the system impact by another 40% in the best case, whereby the achievable benefits strongly depend on process choice, process design and product composition. The biggest climate change impact reduction by chemical recycling is due to avoidance of incineration emissions. Therefore, combining maximum mechanical recycling with carbon capture for incineration may also achieve benefits amounting to more than 80% of the benefits achievable by combining mechanical and chemical recycling.

Quantifying the effect of the Basel Convention Plastic Waste Amendment: How did trade patterns and environmental impacts change?

Monday, 3rd July - 09:15: Plastics: impacts (C0.06 KOG)

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The plastic waste trade has been an opaque business for a long time. Regulations help to increase transparency and strengthen border control to reduce excessive environmental pressure on waste imported countries. One example is China's plastic waste ban in 2017. A new effort has been taken on 1 January 2021was the amendments to the Basel Convention. It promotes the sorted plastic waste trade among the 189 signed parties. If the new rule is effectively implemented, the Basel amendment could considerably change the current plastic waste trade flows as well as related environmental impacts.

Using the UN international trade statistics (UN Comtrade database), we trace and analyse the trade flows of 6 types of plastic waste (HDPE, LDPE, PET, PP, PVC, and PS) among 29 countries for the reference period (2018 - 2020) and the year 2021. Combined with the ecoinvent 3.6 database, we further quantify the related environmental impacts regarding waste transport and treatments.

The results of this hybrid assessment fuel the discussion about to what extent international regulations can shape the global plastic waste trade. The overall impact is compared with other regulations originating from regional or national policies. Besides, the potential environmental dividend of supplying more recyclables in the market is discussed. This work expects to shed light on building a fair, sustainable, and resilient global plastic waste market.

Do bio-based plastics have a lower environmental impact than petrochemical-based plastics?

Monday, 3rd July - 09:30: Plastics: impacts (C0.06 KOG)

Linda Ritzen [1]***, Benjamin Sprecher*** [1]***, Conny Bakker*** [1]***, Ruud Balkenende*** [1]

1. *Delft University of Technology*

Bio-based plastics are gaining attention as a sustainable, circular alternative to the current, petrochemical-based plastics. Bio-based plastics are based (at least in part) on biomass, usually through chemical conversion of carbohydrates, proteins or fats in plants (Harmsen et al., 2013). The environmental impact of plastics can be reduced by using biomass as a resource because plants absorb CO_2 during their growth. Nevertheless, the growth of biomass and its conversion into plastics requires resources and energy. Therefore, it is important to quantify the environmental impact of the production of bio-based plastics using lifecycle assessment (LCA).
Prior studies have found variations in LCA outcomes of bio-based plastics: variations as large as 400% for studies assessing the same plastic (Walker & Rothman, 2020). These variations have been attributed to methodological inconsistencies (Bishop et al., 2021; Walker & Rothman, 2020). While these factors do contribute to large variations of LCA's of bio-based plastics, the existing body of literature does not address the effect of different types of biomass, production locations and assumptions for chemical conversion processes on the environmental impact of bio-based plastics. Uncovering the influence of these factors would provide useful information for the design and the implementation of plastics.
In order to remove methodological differences, we conducted replications of LCA studies reported in literature. During this effort, we found that most LCAs could not be replicated due to lack of transparent data. Bio-based polyethylene (bio-PE) and bio-based polyethylene terephthalate (bio-PET) were the only plastics for which sufficient information was available to make a comparison. Processes and assumptions used for each step of bio-based PE and bio-based PET were considered, including the type of biomass, its conversion into monomers and polymerisation, varying each step to assess its influence on the environmental impact bio-PE or bio-PET production.
By creating a set of methodologically consistent LCAs of bio-PE and bio-PET, we have uncovered that the inconsistencies with bio-based polymers' LCAs reach further than methodologies. The type of biomass and the location determine the amount of energy needed to grow and convert biomass. Assumptions in the chemical conversion processes of bio-based monomers were often found to be either confidential or estimates. In absence of high quality producer information, input data for these processes was estimated based on simulations, varying between publications. Poor quality data in some of the most critical processes in the production of bio-based polymers likely influences many other aspects of the LCA, since they may over- or underestimate the amount of biomass required to produce a bio-based plastic. Weather bio-PE and bio-PET have a higher or lower environmental impact than their petrochemical-based counterpart depends on these assumptions. Until transparent data from producers is available, a reliable assessment of the environmental impact of bio-based polymers will remain impossible.
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Reducing Greenhouse Gas Emissions through Effective Waste Management in a 100% Bio-Based Plastic Market

Monday, 3rd July - 09:45: Plastics: impacts (C0.06 KOG)

ELISABETH VAN ROIJEN [1], ***Sabbie Miller*** [1]

1. *University of California, Davis*

The critical role of plastics in our society is extremely prevalent, especially in times of turmoil: they can serve as a physical barrier to protect from infectious diseases, and help transport food and necessities to individual's in need. Our reliance on plastics will continue to grow as populations expand and new infrastructure is built, supported by their low density, durability, and cost-effectiveness. However, the basic building blocks of plastics as we know them today are inherently unsustainable; they use petroleum-based resources, and their production results in substantial greenhouse gas (GHG) emissions, as well as a myriad of other environmental burdens. Transitioning to bio-based plastics has commonly been touted as a means to move towards a more sustainable future. The bioplastic market has been growing considerably in recent years, with numerous studies examining how to minimize the GHG emissions of bio-based plastics using low-value agricultural byproducts and food waste rather than food crops, such as corn and sugarcane, as a feedstock. However, the growth and research in the bioplastic market have been coupled with a relatively stagnant waste management strategy in many regions. For example, in the United States, the vast majority of their plastics are landfilled; in other regions, plastics are commonly combusted as an energy resource. Although researchers have examined the biodegradation behavior of bioplastics in certain environments, the potential environmental impacts of discarding these materials has not been thoroughly analyzed. In this presentation, the sensitivity of bioplastic life cycle emissions to end-of-life treatments (namely, composting, anaerobic digestion, mechanical recycling, incineration, landfilling, and landfilling with biogas flaring) will be discussed. By combining production and end-of-life GHG emissions of bio-based plastics, preliminary results for a future bio-based plastic market were obtained. It was found that using 100% bio-based plastics rather than petroleum-based plastics would result in nearly the same GHG emissions in 2050, with a substantial fraction of these emissions coming from end-of-life treatment alone. A preliminary assessment of the change in plastic end-of-life emissions resulting from changes in the bioplastic markets (e.g., increased use of bio-based plastics in construction versus packaging applications) will also be discussed. To reach climate change mitigation goals, the carbon sequestration potential of bio-based materials should be maximized and the benefits tied to the best utilization of these resources at end-of-life must be explored. This research will help identify pathways to make the bio-based plastic market more sustainable, enable policymakers to implement effective waste management targets for plastics, and identify current technological gaps.

Global supply chain drivers of agricultural plastic pollution in China

Monday, 3rd July - 10:00: Plastics: impacts (C0.06 KOG)

Chuan Zhao [1]***, Zhengyang Zhang*** [1]***, Kazuyo Matsubae*** [1]

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Background

The prevalent plastics use in agriculture has led to the improved food productivity but leaves simultaneous concerns upon ecosystem health. Most agricultural plastics are single-used and more difficult to recycle relatively to other applications (e.g., building and construction) due to the contamination from chemical fertilizers and pesticides through agricultural activities.

The plastic debris in the arable land, which originated from damage, degradation, and discard, imposes a significant challenge on soil and water safety, threatening the eco-health and the food web base. Great efforts have been made and enable the understanding of mechanisms of decomposition, toxic emissions, and soil-to-water paths of various agricultural plastic debris, contributing to the potential technical innovation that could approach reduced plastic pollution.

Besides, agriculture broadly links the production of plants and animals with domestic and global consumption, either as food to satiate a growing population or for fibers, fuels, medicines, and other supplies in entire industries. Thus, the negative impact derived from agricultural plastic debris can impair food security and safety alongside the entire chains. On the flip side, agriproduct demands and remote socioeconomic activities in every part of the supply chain have been driving agriculture production and associated contamination. Therefore, it is vital to comprehensively illuminate the supply chain drivers of agricultural plastic debris pollution, which provides precise monitoring and management for policy decisions.

China—one of the largest agriculture countries striving to feed its population with limited arable lands—has played an important role involving in the global market. Meanwhile, China topped among the countries utilizing plastic film mulching, consuming more than half of the worldwide plastic films (the most prominent type of agricultural plastic use). With the continuously increasing demand, it is urgently necessary to identify the magnitude of plastic debris leakage into the environment from agriculture, drivers of direct food consumption and indirect supply demand from domestic and global trade. These findings that are yet little acknowledged will help determine the regions and sectors that should prioritize the promotion of technological innovations, guide consumption behavior towards sustainability, and improve production efficiency in related sectors.

Research objective

- To identify the hotspots of plastic debris pollution from agricultural production across China;
- To illuminate the domestic and international supply chain drivers of agricultural plastic debris pollution located in China.

Method

- Based on the information on agriculture activity across 31 provinces in mainland China, a bottom-up approach is utilized to estimate the plastic debris of various polymers associated with crops, livestock, and fisheries production.
- Adopting the environmentally-extended input-output analysis, we link the agricultural plastic debris pollution inventory into a nested Chinese (provincial level)-global multiregional input-output table to calculate the pollution driven by both local and international final demand related to the full range of industries.

Expected results

The total amounts of agricultural plastic debris remaining in the farming territories of each Chinese province with resolutions at farming and polymer categories are envisioned, and the most severe pollution related to the location, farming, and polymer type will be found. In addition, we propose to figure out the respective proportions of agricultural plastic debris pollution in certain provinces driven by the final demand of other provinces/nations (sectors). The findings would provide multiple implications for policy decisions to monitor agricultural plastic debris in Chinese provinces and for global coordination.

USING DATA ENVELOPMENT ANALYSIS TO EVALUATE MARINE PLASTIC POLLUTION IN THE PERUVIAN INDUSTRIAL FISHERY.

Monday, 3rd July - 10:15: Plastics: impacts (C0.06 KOG)

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The Peruvian fishing industry is third worldwide thanks to its abundant stock of Peruvian anchoveta (*Engraulis ringens*), which is mainly destined for the production and exportation of fishmeal and fish oil (FMFO). Anchoveta stocks are primarily targeted by a large purse seining fleet with a wide range of variability in terms of operational capacities and efficiencies at sea. Moreover, the anchoveta-related fishing industry is highly regulated; however, attention is mostly focused on stock availability and sustainability rather than on other environmental impacts such as those related to solid waste generation and greenhouse gases emissions. Nonetheless, marine plastic pollution has recently gained massive worldwide attention due to its persistence and the consequences it has on marine biota and human health. Despite this interest, methodologies and information for its assessment are still lacking or currently under development. Global data suggests that the fishing industry is responsible for approximately 10% of all marine plastic litter, making it the biggest ocean-based source of marine plastic pollution. Thus, the main objective of this study is to assess the environmental performance of the Peruvian industrial fishery, with special attention to plastic waste generation, management and subsequent emission to the ocean. For this, Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA), a linear programming nonparametric method, were combined in the so-called 5-step LCA+DEA method to analyze the relative environmental efficiency of a group of purse seining vessels targeting anchoveta for FMFO production. LCA+DEA models have been largely used to analyze environmental scores and transition efficiencies from carbon intensity industries, whereas in this study the approach is shifted, focusing primarily on marine plastic pollution. The DEA matrix is developed with information of 270 purse seiners with 1 output and 4 inputs, and is based on a single purse seining vessel as a decision-making unit (DMU). The output considered is the total landed anchoveta for FMFO production. The first input, fuel consumption is taken directly from the operational life cycle inventories. The remaining inputs refer to multiple related operational inputs displaying similar roles or behaviors within a vessel and are clustered accordingly. The second input is related to marine plastic emissions considering abandoned, lost or otherwise discarded fishing gear (ADLFG); antifouling polymer emissions; and plastic emissions due to food and beverages consumption while at sea. Marine pollution results are detailed and distinguished by plastic polymer and emitted particle size. The third is related to maintenance and construction information, including hull maintenance, lubricants and other materials involved. Finally, the fourth cluster considers additional inventory data from the use phase (i.e. refrigerants use and leakage). Fuel use intensity (FUI) resulted in 19.8 liters, ADLFG amounted up to 373 g, while antifouling plastic polymer emissions 781 mg. These preliminary outcomes are average results for the entire sample of vessels, using 1 metric ton of landed anchoveta as a functional unit. This study is still under development and it will be further advanced as the results obtained will be used to analyze the ecoefficiency of the reduction industry in Peru, which depends greatly of the environmental performance of the fishing stage of the process and also tackle the challenge to address plastic pollution in food systems. Finally, it is expected that the results obtained serve as benchmarks for future fishing and FMFO studies in the region.

Special Session: Backcasting and Scenarios for Sustainability Transitions

A design framework of backcasting towards developing a users' guide

Monday, 3rd July - 09:00: Special Session: Backcasting and Scenarios for Sustainability Transitions (B0.16 KOG)

Yusuke Kishita [1], ***Mattias Höjer*** [2], ***Jaco Quist*** [3]

1. *The University of Tokyo,* ***2.*** *KTH,* ***3.*** *TU Delft*

Backcasting is increasingly used to address sustainability issues both in academic research and in practice. For example, many backcasting scenarios have been developed in energy sectors to achieve carbon neutrality. While many studies are framed as "backcasting studies", there is still confusion in terms of the exact meaning and a variety of definitions, approaches, and processes to execute backcasting. Aiming to help people plan and use backcasting, this paper develops a design framework of backcasting based on a literature review and the authors' experiences. Results of our literature review showed that backcasting has been applied in diverse domains, such as energy, consumption and lifestyle, transportation, water, and cities. From a methodological viewpoint, many scholars proposed backcasting-related methods in the literature, which can be classified into three types: target-oriented, path-oriented, and participatory backcasting. From the review results, we found that backcasting has been used in many domains to address sustainability issues, where different methods and processes are applied. However, it has not yet been systematized how backcasting methods are planned and used to address a given problem. Based mainly on the authors' own methodological frameworks and experiences, we develop the design framework consisting of five key questions: (i) When backcasting is used, (ii) what type of backcasting is chosen, (iii) how backcasting is applied, (iv) to what results backcasting leads, and (v) what outcomes and impacts are aimed for. A few simple examples are used to demonstrate how the developed framework works and to discuss some challenges to be tackled for further research.

This abstract is proposed as part of a special session proposal proposed by Jaco Quist, Yusuke Kishita and Mattias Hojer entitled "Backcasting and Scenarios for Sustainability Transitions." The first author, YK, acknowledges financial support from the Environment Research and Technology Development Fund (JPMEERF20223R04) of the ERCA by the MOE, Japan, Japan Science and Technology Agency (JST) as part of SICORP (JPMJBF2203), and JSPS KAKENHI (21H01234 and 23H03676).

Backcasting and Visioning for Sustainability Transitions and Industrial Ecology: Comparing Methods, Cases and Impact

Monday, 3rd July - 09:15: Special Session: Backcasting and Scenarios for Sustainability Transitions (B0.16 KOG)

Jaco Quist [1]

1. *TU Delft*

Visions are important in sustainability transitions and Industrial Ecology. Their role, functions and use needs further study, both conceptual and empirical, including relevance for governance as well as transdisciplinary and transformative practices. A distinction can be made between (i) visions in long-term developments and transitions, also used to explain socio-technological change, (ii) generating visions through interactive learning and interaction among groups (of actors) and transdisciplinary contexts, and (iii) assessing visions through vison assessments to explore possible value conflicts and other value-driven and interest-driven differences among actors and stakeholders in emerging transitions.

This paper will focus on methods for making visions for Sustainability Transitions and Industrial Ecology as part of backcasting and transition management frameworks addressing the research question 'what methods can be applied for visioning and visions for Sustainability Transitions and what factors and conditions determine their quality and impact?' Two major approaches for making visions are backcasting and transition management, though other participatory visioning approaches can be found too. The paper will first review recent developments of vision-based approaches through an overview of the literature and building on research work and projects of the author.

Key results include an inventory on methods and cases using these methods showing how visions can be made, based on a range of studies and projects conducted by the author, yet complemented by additional examples from sustainability science, sustainability transitions and sustainable futures studies. The inventory of visioning methods includes: (i) creativity methods, such as brainstorming, in combination with clustering, (ii) problem structuring approaches, as often used in transitions management, (iii) using guiding questions and facilitation, (iv) elaboration of visions start via setting targets, (v) Morphological analysis, in the sense of creating diversity for different dimensions of the system under study and consistency analysis to generate vision, (vi) Q- methodology, a method from social sciences that is applied to study diversity in viewpoints, but which can also be used to generate future perspectives and may yield up to five or six future visions, and.(vii) Making narratives and imaginaries.

Cases and examples are compared on their visioning methods, quality of results, not only content and analytical results, but also process results with regard to learning, participation and commitment, as well as how generated knowledge is used in decision making and whether there is spin-off and follow-up by putting results into practice. It is concluded that a range of visioning methods are available, but that further comparative research is needed to relate impact and to the process and applied method.

The paper consists of an introduction, a literature overview of visioning approaches, a section describing main visioning methods, a discussion section developing a framework for methodological characteristics and criteria for application before drawing conclusions.

This abstract is proposed as part of a special session proposal proposed by Jaco Quist, Yusuke Kishita and Mattias Hojer entitled "Backcasting and Scenarios for Sustainability Transitions.

Backcasting sustainable transport futures for Sweden 2035

Monday, 3rd July - 09:30: Special Session: Backcasting and Scenarios for Sustainability Transitions (B0.16 KOG)

Mattias Höjer [1]***, Jonas Åkerman*** [1]***, Hampus Berg Mårtensson*** [1]

1. *KTH*

Together with Buildings, Food and Industry, the Transport system is a critical part to deal with in terms of reducing greenhouse gas emissions. Many technical solutions are underway in the transport system, with electrification of the car fleet being among the most evident. For air transport, the sustainable solutions are further ahead. Less focus is spent on transport infrastructure and travel demand.

In this paper we develop scenarios for Swedish transport that are in line with a strong reduction of GHG-emissions until 2035 and present corresponding energy use. We use a backcasting approach with goal-fulfilling images of the future. The paper brings in all emissions from the system, including indirect emissions from e.g. construction of vehicles and infrastructure. Even though the calculations include the whole system, the paper chooses to focus on three specific parts, where we also contribute with new calculations:

- Potential emission reductions through change of technology and fuels
- More efficient use of infrastructure and vehicles
- Reduced commuting trips and air travel

The first of those are based on a combination of literature studies of current technologies, combined with an analysis on how much technological changes can support reduced GHG-emissions by 2035.

The second part emphasises the importance of using the existing system more efficiently and includes two main topics. The first investigates the opportunities for using the railway network more efficiently. This can be done e.g. through longer trains and new signalling systems. The second topic looks at the use of roads and considers e.g. traffic management through congestion charging and shared vehicles.

The third part brings up travel demand and does this with regard to two specific travel types – commuting and air travel. For commuting a quantitative analysis regarding the Swedish labour market and the opportunities for various working groups to work space-independently a certain amount of their time, is done. For air travel, business trips are treated separately from leisure trips, and we look into environmental effects of reducing mainly business trips, but also add comments of various leisure trip developments.

The presentation results in new data regarding greenhouse gas emissions and energy use for the whole Swedish transport system. It also shows that commuting, business travel and school trips together stands for 45% of GHG emissions from car travel in Sweden. Moreover, it lays out arguments stating that space independent work can cut car commuting considerably, and provides sample calculations regarding the long-term potential for substituting business air travel with digital solutions. We also show how a more efficient use of infrastructure and vehicles can reduce life-cycle GHG emissions as well as reducing public expenditures.

Even though the paper is using Swedish data as a starting point, it also includes European comparisons in order to support a discussion regarding to what degree the general findings are valid for other transport systems than the Swedish. In most cases, the starting points in this paper are valid for other countries as well, but the background data would need to be adjusted to a country-specific level.

☐ Digitalizing Backcasting Scenario Design in Toyama City, Japan

Monday, 3rd July - 09:45: Special Session: Backcasting and Scenarios for Sustainability Transitions (B0.16 KOG)

Taiki Yokota [1], ***Yusuke Kishita*** [1], ***Kazumasu Aoki*** [2]

1. The University of Tokyo, 2. University of Toyama

Designing backcasting scenarios is a powerful method for creating sustainable visions and developing strategies and policies to achieve the visions. When designing backcasting scenarios on a regional scale, workshops are often used to reflect the knowledge and opinions of local stakeholders. On the other hand, the recent covid pandemic has accelerated the introduction of digitalization to arranging and operating backcasting scenario workshops. Some scholars reported that using digital tools at workshops has potential in various aspects. However, it is still unclear how to utilize digital technology effectively in the scenario design process, particularly in backcasting. This paper aims to discuss the challenges and opportunities to digitalize backcasting scenario design based on a literature review and our own backcasting scenario practice in Toyama City, Japan. We compare two workshops of participatory backcasting scenario design, i.e., one is a physical workshop in 2016 and the other is an online workshop in 2021 in which digital tools (i.e., web conference platform, online whiteboard, and simulation tool) were used. Results showed that online workshops and digital tools have a positive influence on the sharing and management of information and the efficiency of design process. However, it was difficult for participants to communicate and discuss with one another during online workshops. We also open up discussions on the opportunities of using virtual reality (VR) to solve this problem, which will be reported in the conference.
This abstract is proposed as part of a special session proposal proposed by Jaco Quist, Yusuke Kishita and Mattias Hojer entitled "Backcasting and Scenarios for Sustainability Transitions."

Renewable Energy Scenarios for South Kalimantan using Participatory Backcasting: Methodology and First Results

Monday, 3rd July - 10:00: Special Session: Backcasting and Scenarios for Sustainability Transitions (B0.16 KOG)

Indra al Irsyad [1], *Jaco Quist* [1], *Jannis Langer* [1], *Kornelis Blok* [1]

1. TU Delft

Indonesia is the world's fourth-most populous country and is set to become the world's fourth-largest economy by mid-century. This is reflected by that in the last two decades, Indonesia's electricity demand has grown more than 6% annually and it is expected to rise at a similar rate until 2050 driven by economic growth of around 5% annually. Unfortunately, Indonesia's energy mix is still dominated by fossil fuels, especially coal, extracted on the islands of Kalimantan and Sumatra. Moreover, renewable energy targets for 2030 are just above 20%, despite that Indonesia has committed to net zero electricity in 2021 at the COP26 in 2021. Further renewable energy (RE) integration, replacing fossil fuel-based energy, is necessary to bring about a renewable energy transition and to meet climate targets. Fortunately, Indonesia has a huge potential for renewable energy from hydro, wind, solar, geothermal, biomass and ocean energy (Langer et al, 2021). Until recently only geothermal, biomass and hydropower were being scaled up, though much higher capacity has been planned towards 2050 (Langer et al, 2021). The potential of renewable energy sources as well as renewable energy futures and pathways towards renewable energy futures are currently studied in a collaborative project of TU Delft and IT Bandung on regional energy transitions in Indonesia using backcasting and related approaches (Indonesia Regional Energy Transition TU Delft, Quist, 2013).

The proposed paper reports on part of the project that focuses on developing a methodology using participatory backcasting (Quist, 2013) to generate 100% renewable energy futures at the provincial level and will present preliminary results for the province of South Kalimantan. It will use renewable energy potential analysis at the provincial level in combination and views on possible energy futures collected via stakeholder interviews to generate renewable energy futures that will be subject to further discussions with stakeholders in order to co-create pathways and policy recommendations.

One of the intended outcomes of the project is a methodology that can be replicated at other provinces and regions. The province of Kalimantan makes an interesting case as on the one hand it is the province having the third largest coal reserves (after East Kalimantan and South Sumatra, respectively), while on the other hand the province has the ambitious vision to be a frontrunner on renewable energy utilizations as stated in South Kalimantan's Regional Energy General Plan (abbreviated as RUED in Bahasa Indonesia).

This abstract is proposed as part of a special session proposal proposed by Jaco Quist, Yusuke Kishita and Mattias Hojer entitled "backcasting and Scenarios for Sustainability Transitions.

References:

Langer, J., J. Quist, K. Blok (2021) Review of renewable energies potentials in Indonesia and their contribution to a 100% renewable electricity system, Energies 2021, 14(21), 7033.

Quist, J (2013) Backcasting and Scenarios for Sustainable Technology Development, in: K.M. Lee, J. Kauffman (Eds.) Handbook of Sustainable Engineering, Springer, pp. 749-771.

Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 2)

From Disruptions to Opportunities: The Impact of Covid-19 on Industrial Waste Trading in China

Monday, 3rd July - 12:00: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 2) (A0.51 KOG)

Xiao Li [1], ***Xuezhao Chen*** [1], ***Wen Liu*** [1], ***Dong Liu*** [1], ***Runlin Yang*** [1]

1. *Xi'an Jiaotong University*

The Covid-19 pandemic has caused significant disruption to the global economy, including the trade of industrial waste as secondary resources. This study examines the impacts of the pandemic on the industrial waste trading activities of manufacturers in Guangdong Province, a leading economic region in China, and its effects on resource sustainability. The study employs a combination of quantitative methods, such as regression discontinuity designs and event studies, and qualitative research methods to gather and analyze data from a sample of manufacturers in the waste trading market. The results indicate that the pandemic has led to a sharp decrease in demand for industrial waste as a secondary resource, resulting in lower prices and reduced availability of waste materials. Supply chain disruptions and workforce shortages have also hampered the ability of manufacturers to process and manage waste. However, the study also reveals positive outcomes, including manufacturers' efforts to adopt innovative solutions to sustain waste trading and utilization. The study concludes that the Covid-19 pandemic has had a profound impact on the industrial waste trading sector in China and that further research is required to fully comprehend these effects and their implications for resource sustainability, particularly in the medium and long-term. The findings of this study hold important implications for policy makers, business leaders, and academics working in the fields of eco-industrial development and industrial ecology. By fostering sustainable waste management and resource circularity, this research seeks to contribute to the creation of a more sustainable production system in the aftermath of the Covid-19 pandemic.
Note: This abstract could contribute to the proposed special session "Systemizing Industrial Waste Management for Resource Security and Carbon Neutrality: New Challenges and Opportunities".

City-level inequalities in sustainable development

Monday, 3rd July - 12:15: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 2) (A0.51 KOG)

Ruoqi Li [1], ***Yidan Zhou*** [1], ***Miaomiao Liu*** [1], ***Jun Bi*** [1]

1. State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing, China

City-level efforts are critical to addressing current global challenges such as poverty eradicating poverty, implementing climate change actions, and encountering energy crises. In order to quantify progress in addressing various global threats, the United Nations adopted 17 Sustainable Development Goals (SDGs). Previous studies have assessed the progress towards a sustainable world at global, national, and sub-national levels based on the framework of SDGs. However, to date, little is known about sustainable development progress at the city level. As the world's second-largest economy, China is facing unprecedented challenges of sustainable economic transformation and regional inequalities. In this study, for the first time, we evaluate the progress of sustainable development in 309 cities and 4 provinces in China by integrating a series of databases, including China's Environmental Statistical Database (CESD), carbon emission datasets and energy inventory from CEADs, etc. Given the possible impact of trade on the economy and sustainability, we introduced a city-level multi-regional input-output (MRIO) model to assess the trade's impact on 20 SDG targets quantitatively. These targets involve 10 SDGs, including Zero Hunger (SDG 2), Good Health and Well-being (SDG3), Clean Water and Sanitation (SDG6), Affordable and Clean Energy (SDG 7), Decent Work and Economic Growth (SDG 8), Industry, Innovation and Infrastructure (SDG 9), Sustainable Cities and Communities (SDG 11), Responsible Consumption and Production (SDG 12), Climate Action (SDG 13), Life on Land (SDG 15). This is a submission to the special session "Urban Climate Action toward Carbon Neutrality".

Greenhouse gas emissions inventory of natural gas pipeline incidents in the United States and Canada from 1980s to 2021

Monday, 3rd July - 12:30: Special Session: Urban Climate Action toward Carbon Neutrality with enhanced Resource circularity (Part 2) (A0.51 KOG)

Hongfang Lu [1]

1. *China-Pakistan Belt and Road Joint Laboratory on Smart Disaster Prevention of Major Infrastructures, Southeast University,*

Natural gas is believed to be a critical transitional energy source. However, natural gas pipelines, once failed, will contribute to a large amount of greenhouse gas (GHG) emissions, including methane from uncontrolled natural gas venting and carbon dioxide from flared natural gas. However, the GHG emissions caused by pipeline incidents are not included in the regular inventories, making the counted GHG amount deviate from the reality. This study, for the first time, establishes an inventory framework for GHG emissions including all natural gas pipeline incidents in the two of the largest gas producers and consumers in North America (United States and Canada) from 1980s to 2021. The inventory comprises GHG emissions resulting from gathering and transmission pipeline incidents in a total of 24 states or regions in the United States between 1970 and 2021, local distribution pipeline incidents in 22 states or regions between 1970 and 2021, as well as natural gas pipeline incidents in a total of 7 provinces or regions in Canada between 1979 and 2021. The study can improve the accuracy of regular emission inventories by covering more emission sources in the United States and Canada and provide essential information for climate-oriented pipeline integrity management.

Buildings and construction (short presentations)

Tracking five decades of global sand and gravel flows and stocks

Monday, 3rd July - 12:00: Buildings and construction (short presentations) (C1.31 KOG)

Shurong Zhuang [1]***, Qiance Liu*** [2]***, Ruishan Chen*** [3]***, Gang Liu*** [2]

1. *East China Normal University; University of Southern Denmark,* ***2.*** *University of Southern Denmark,* ***3.*** *Shanghai Jiaotong University*

As the materials are fundamentals for our socioeconomic systems, sand has become the most consumed construction material among all anthropogenic materials in quantity and is expected to keep the trend in 2060. Although sand can be provided in multi-sources (e.g., river sand deposits, terrestrial hard rock deposits, and marine aggregates deposits), the shortage crisis for sand has attracted increasing attention from both academic and societies. Tracing the flows and stocks of sand would be the basis to mitigate the shortage of sand. However, an explicit picture of sand supply and demand in the world is still not exist. A growing body of literature focuses on mapping the flows and stocks of sand. But there are still some knowledge gaps remain: a) lacking a higher resolution of flows and stocks at global and national levels; b) how the sand dynamics, especially for the future, is still insufficiently discussed; c) the environmental impacts associated with the sand cycles have rarely been examined. To fill the above-mentioned knowledge gaps, we develop an MFA model to estimate the historical in-use sand stocks for all the countries during 1970-2020 and predict the future sand demand in different scenarios. With sand mining transitions, we simulate energy use and CO_2 emissions in different energy use strategies, considering energy efficiency and price changes. Our results revealed explicit pictures of global and national sand cycles from 1970 to 2050. We found that the building sector was and will be the world's most dominant consumer of sand. At the same time, not all regions or countries will meet the shortage crisis due to the world's unbalanced supply and demand structures. Developing countries (e.g., China and India) will continue to drive the global consumption of sand. Finally, with the material preference changes from unconsolidated sand to crushed rock to meet society's demand for sand, the environmental impacts will increase. Therefore, we appeal to all nations should collaborate to implement effective measures (e.g., intensive use, recycling of construction waste, finding new substitutes) to solve the global sand shortage crisis.

A comparative life cycle assessment of a cross-laminated timber and a lightweight steel frame building, a case study in the Netherlands

Monday, 3rd July - 12:07: Buildings and construction (short presentations) (C1.31 KOG)

Mingming Hu [1]***, Wesley Simon Grul*** [1]***, Bernhard Steubing*** [2]***, Mike Slootweg*** [3]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden, 2. CML Leiden, 3. Leiden University

The Netherlands has faced rapidly increasing housing demand and at the same time the world is facing a climate crisis and the Netherlands has pledged to decrease its emissions by at least 50% in 2030 in respect to 1990. The country therefore need reduce the impact of new built houses to be able to build more while reducing the total emissions.

Currently most Dutch houses are built with reinforced concrete which causes carbon emissions related to cement production. Building houses with cross-laminated timber panels or lightweight steel frames are proposed alternatives with a lower expected carbon footprint. This study was set up to perform a life cycle assessment of a steel and a timber building to compare their impact and find out under which circumstances building with steel or timber is a more sustainable option.

It has been found when including the climate impact of construction, the treatment of waste, end-of-life benefits and carbon storage, the timber building performed better than the steel building in every scenario regarding global warming. However, waste treatment, end-of-life benefits and carbon storage are all dependent on future processes and emissions happening after 2030. When only the construction is included, the steel building outperformed the timber variant in the expected and best-case scenario. For this reason, building more houses with lightweight steelframes produced with at least 50% recycled steel would be the most beneficial for the Netherlands to reach its 2030 climate goals. When taking a longer timespan into consideration, timber buildings are the preferred choice due to the carbon storage effect, as long as the forests are replanted sustainably.

The outcomes of this study may influence decision making depending on the weight the Dutch government gives to its climate goals of 2030 versus its total impact on climate change. Constructing steelframe houses may reduce construction emissions by 4% compared to timber by 2030 but would result in 64% more emission in 2100 due to the missed-out carbon storage. In general, the construction industry can improve a lot by increased use of low-carbon alternatives such as lightweight recycled steel and biobased materials.

Estimating Embodied and Operational Emissions of Residential Building Stock in Western Asia and Northern Africa: A Comparative Study

Monday, 3rd July - 12:14: Buildings and construction (short presentations) (C1.31 KOG)

Sahin AKIN [1], ***Aida Eghbali*** [1], ***Chibuikem Nwagwu*** [1], ***Niko Heeren*** [2], ***Edgar Hertwich*** [1]

1. Norwegian Univ. of Science and Technology, 2. City of Zurich

The building and construction sectors combined contribute to nearly 40% of both direct and indirect CO_2 emissions. Among various building types, residential buildings play a crucial role, accounting for 21% of global final energy consumption. Furthermore, their construction-related emissions in 2015 amounted to 4 Gt CO_2e, with over 60% attributed to materials. Global energy and raw material use are estimated to rise significantly by 2050, with construction materials experiencing the highest increase in usage rate. This trend is particularly pronounced in developing countries, driven by rising income, increased access to electricity, and urbanization. To effectively address and mitigate regional emissions originating from residential building stocks in the developing world, conducting country-specific studies that consider the unique building factors and their environmental impacts is crucial. Western Asia and Northern Africa are home to many developing countries with distinct architectural features, yet their building stocks have not been thoroughly studied in the past. To bridge this research gap, this study focuses on the national building stocks of five countries (Turkey, Egypt, Iraq, Saudi Arabia, and Jordan) that represent the diversity of the regions. A bottom-up archetype-based stock modeling approach is developed and applied to the selected building stocks, taking into account a wide variety of archetypes that consider different climate, architectural, and economic characteristics within the region. The study integrates industrial ecology methods, including life-cycle impact assessment (LCIA) and building energy models, to estimate the current material, energy, and CO_2 emission intensities of the building stocks. The simulation of the developed energy models is performed using the BuildME framework, which enables the calculation of building material and energy use. The study concludes by utilizing the material and energy intensities of the building stocks to calculate both embodied and operational CO_2 emissions. By incorporating a wide range of factors such as population size, urbanization, climate conditions, and policy frameworks, the five case studies provide a comprehensive understanding of the embodied and operational emissions in residential building stocks in Western Asia and Northern Africa. This comprehensive and comparative assessment on a larger scale can assist professionals and decision-makers in comprehending the current impacts of climate change, while also facilitating the implementation of diverse policy instruments to shape the future of these regions.

Assessing the Construction Materials Intensities in Buildings: A Historical Case Study in the City of Debrecen

Monday, 3rd July - 12:21: Buildings and construction (short presentations) (C1.31 KOG)

Faisal Aldebei [1], ***Attila Harangi*** [1]

1. University of Debrecen

Material Intensity Coefficient (MIC) is an essential metric used in material flow analysis (MFA) to understand the amount of material contained in a specific product or structure. In the context of building stock, MIC databases are necessary for bottom-up material stock studies (Gontia et al., 2018) as they provide information about the amount of materials contained in different building types. This information can be used to understand the flow of construction materials, support decision-making for material utilization and waste management, and inform policies and initiatives aimed at transitioning towards a circular economy. (Lanau et al., 2019)
The primary objective of this study is to develop a comprehensive MIC database for residential and nonresidential buildings in Debrecen, Hungary's second largest city. The study aims to understand the amount of materials present in different building types, analyze historical trends in material intensity, and compare the results with similar geographical regions. To conduct the study, the building stock was classified based on archetypes (Negendahl et al., 2022). The authors then analyzed a sample of residential and nonresidential buildings in Debrecen. The population of buildings includes 1445 surviving historical buildings. The amount of materials present in each sampled building was investigated. The authors used several data sources such architectural data, building permits, brick production records and field surveys to determine the MICs for different building elements.
The results of the study showed specific trends in material intensity and composition in Debrecen's residential and nonresidential buildings. The authors found that historical events and technological changes had a considerable impact on MICs. This study provides valuable information about the material intensity and composition of residential and nonresidential buildings. The results highlight the importance of further analysis of MIC databases for different geographical regions to achieve accurate stock estimations. The MIC database developed in this study will be a valuable resource for future studies in this area.

Defining Pathways to Carbon Neutral Concrete: A Life Cycle Carbon Assessment of Biochar Concrete

Monday, 3rd July - 12:28: Buildings and construction (short presentations) (C1.31 KOG)

Harn Wei Kua [1]***, Alvin Wei liang Ee*** [1]***, Hsien Hui Khoo*** [2]

*1. National University of Singapore, 2. A*Star*

In the past one and a half decade, encouraging progress has been made in understanding the life cycle environmental impacts of biochar, and the potential of using biochar as a partial cement in concrete as a mean of reducing the net carbon emission of concrete. For example, it was found that recycling stover waste as feedstock for producing biochar from pyrolysis can yield a net negative (-846 $kg_{CO2\text{-}e}$ per kg of feedstock) carbon emission (Roberts et al, 2010).

For the past 10 years, applying biochar in concrete has developed into a sustainable method of "greening" concrete with a net carbon negative industrial by-product. An attributional life cycle assessment with expanded boundary was employed to examine the life cycle global warming potentials (GWPs) of $1m^3$ of biochar concrete, containing wood-based biochar at 2%wt (i.e., by weight of cement). Carbon reduction is defined as the sum of the CO_2-equivalence that is "locked" in the biochar, avoided carbon emissions, CO_2 removal (due to Accelerated Carbonation Curing (ACC) of concrete and onsite carbon capture and sequestration (CCS)), reduction of concrete components' size, use of recycled aggregates and partially replacing cement with recycled pozzolanic materials. Avoidance considered included CO_2 emission reductions due to the cement avoided (2% of the total cement mass), incineration of wood waste in the incineration plant, and the avoided fossil fuel-based electricity required to run the pyrolyzer.

It was found that by using only 2%wt of biochar in concrete (40 MPa), there is a potential to reduce the net GWP of conventional concrete by about 6.38%. This analysis also revealed the conditions needed to render concrete net *carbon neutral* or *even carbon negative* in the future.

For example, if the dosage of biochar in concrete is increased to 5%wt, the net GWP of the binder and aggregates in the concrete is reduced by 40% and 50% respectively by using recycled alternatives (e.g. rice husk ash and blast furnace slag as binders and recycled gravel as aggregates), and the size of the concrete components is reduced by 40% due to the strength-enhancing effect of biochar, then CCS must remove at least 0.40 kg_{CO2} per kg of cement and ACC must remove at least 3 moles (or about 130 g) of CO_2 per kg cement in order for concrete to be theoretically carbon neutral. However, if CCS is not an option and reduction of concrete component's sizes are impossible, with the current state-of-the-art more sustainable aggregate and binder alternatives, dosage of biochar in concrete has to be increased to 28%wt to render concrete carbon neutral. Besides these two scenarios, several others will also be examined and the key engineering, economic and policy-related challenges and opportunities will be discussed.

Patterns of building material stocks' service provisioning and resource productivity across Europe's cities

Monday, 3rd July - 12:35: Buildings and construction (short presentations) (C1.31 KOG)

Tomer Fishman [1], ***Yoav Peled*** [2]

1. Leiden University, CML, 2. Reichman University

Buildings act as provisioning systems between the natural environment and human needs. Building stocks provide innumerable societal services, including dwellings, transportation, communication, and capital. They determine the shapes of cities and have major roles in shaping quality of life and the urban environment. Meanwhile the environmental impacts of construction materials are formidable, including large contributions to annual anthropogenic greenhouse gas emissions, huge volumes of construction and demolition wastes, and rapid land use change through urbanization, excavation, and demolition waste sites. The efficient usage of this material stock to provide services to society is thus key to sustainability. Nevertheless, it has been challenging to assess the capability of buildings to provide socioeconomic services on a large scale and compare these capabilities between cities.

In this presentation we comparatively assess the service-provisioning of building stocks for the entirety of Europe. We use our previously estimated spatially-explicit material stocks accounts of Europe, aggregated to subnational administrative divisions in 37 countries. We identify and describe patterns of material stock accumulations across Europe using several types of machine learning approaches.

We identify that cities with very high population densities above 7000 people per square km, including Paris, London, Brussels, Athens, and Bucharest have quite low material stocks per person (ca. 100 kg per capita). This suggests that more urbanized dense settlements benefit from improved resource efficiency – they manage to support higher populations using less materials – which has important implications for sustainability. In comparison, cities with low and medium population densities have high variability of ranges of materials per person and can be grouped into unique clusters which transcend geographical and political boundaries.

At the level of provinces and counties we combined our material stock data with population, GDP, employment rates, and life expectancy data to identify general typologies of service provisioning. There are relatively distinct geographical patterns to the clusters, such as regions with high material stocks, high populations, and high economic activity (measured in GDP) mostly in the south of Europe, compared to regions that achieve this with lower material stocks and populations including mostly central Europe, most of the British isles, and north Europe. In comparison, regions in east Europe have low populations, GDP, life expectancy, and employment rates, yet relatively high material stocks – indicating a less efficient use of their material stocks.

These results suggest pathways toward more sustainable material usage by identifying exemplary cities that already utilize their existing material stocks in more efficient ways. The identified typologies can serve to compare and benchmark different regions for setting targets and accompanying policies towards more efficient use of material stocks.

Circular economy (short presentations)

Systems framework and quantitative methodology to assess polymer circularity

Monday, 3rd July - 12:00: Circular economy (short presentations) (A1.44 KOG)

Basuhi Ravi [1], ***Karan Bhuwalka*** [1], ***Richard Roth*** [1], ***Elsa Olivetti*** [1]

1. Massachusetts Institute of Technology

There are many limitations to polymer circularity today: from the collection bottleneck (supply) to reprocessing challenges (process technology) and appropriate secondary use opportunities (demand). Without placing these limitations in the broader context of the recycling system at large, we cannot resolve them effectively or in time to address the growing concerns around plastic production and waste management. We propose a shared market-based framework for understanding feasibility, sustainability, and viability of recycling activities that can be generalized to different polymers, use sectors, and geographies. We outline the significance of this shared framework using an assessment of PET circularity in the United States and visualize how policies that impact supply and demand can co-evolve to improve circular outcomes within technological constraints. We further discuss how this framework can be used to inform policymaking by evaluating circularity incentives such as recycled content mandates and eco-modulation of extended producer responsibility fees. The utility of such a framework depends on data availability, sharing, and aggregation from various stakeholders. In this view, we point out data gaps that must be addressed to fully leverage the framework.

Modelling European steel scrap availability – Underlying assumptions, quality constraints and challenges for establishing a circular economy

Monday, 3rd July - 12:07: Circular economy (short presentations) (A1.44 KOG)

Carolin Hundt [1], *Frank Pothen* [1]

1. Ernst-Abbe-Hochschule Jena University of Applied Sciences

In order to decarbonize the energy-intensive steel sector and to establish a truly circular economy in European steelmaking as outlined in the *European Green Deal* (2019) and the *Circular Economy Action Plan* (2020), the current and future steel scrap supply in the EU needs to be accurately mapped with regards to its quantity, quality, sectoral and spatial distribution. A contrastive overview of the varying assumptions and results in the scientific literature is thus beneficial to facilitate sustainable European steelmaking and joint policymaking beyond the national scale.
The objective of this research is a direct comparison of presumed influencing factors, predicted quantities, and quality constraints in previous research on steel scrap. We conduct a model comparison based on recent studies, most of which are material flow analyses that quantify the scrap supply in Europe or globally, with a time frame until 2030 or 2050, and which often consider multiple scenarios. The aim of this comparison is to shed light on the aspects commonly factoring into scrap projections and their influence on the overall future development. Those determinants of future scrap availability include factors such as end-of-life recycling rates, lifetime assumptions of steel products specific to different sectors, material diffusion and remelting losses, or steel stock saturation levels. As a secondary effect, those determining factors may themselves be subject to change over time, for example if CO_2 pricing, mandatory recovery quotas or digital logbooks for buildings are implemented and consequently increase the post-consumer recycling rate. Based on the diverging parameter choice, estimates of future post-consumer scrap supply in Europe vary substantially. The same holds true for the ratio of fabrication scrap and post-consumer scrap or the sectors in which they are predicted to accumulate.
Another crucial aspect of the future scrap supply is its expected quality or purity. Due to the accumulation of tramp elements in post-consumer steel scrap, most notably copper and tin, end-of-life scrap cannot be reused or recycled for all purposes. This will pose a challenge specifically for the metal goods and automobile sectors which rely on high-quality steel. Steel used in construction is more tolerant against accumulations but not indefinitely so. A majority of studies acknowledges that low-purity scrap with limited usability will be the dominant form of post-consumer scrap in the coming decades. Possible solutions of this challenge to the circular economy require technological innovation (product and materials design, improved material detection and automated sorting) as well as economic incentives (market regulations, price mechanisms, recycling incentives).

Two general tendencies are indicated by most of the studies: rising amounts of post-consumer steel scrap related to advancing levels of in-use steel stocks along the process of industrialization and increasing levels of material impurities paired with the loss of critical alloying elements. However, a detailed report of the respective assumptions, predicted quantities and quality categories is needed to better assess the challenges associated with transitioning the steel market into a sustainable circular economy with a reliable supply of necessary steel grades. A solid data foundation for Europe is vital if the European Union as well as major economic stakeholders are to act jointly and decisively for the implementation of this ambitious goal.

The environmental profile and cost benefit analysis of different linear and circular End-Of-Life management of PV Waste in South Korea

Monday, 3rd July - 12:14: Circular economy (short presentations) (A1.44 KOG)

Minhee Son [1]***, Kendra Ho*** [1]***, ojasvee arora*** [2]

1. *Energy Studies Institute, National University of Singapore,* ***2.*** *National University of Singapore*

The demand for solar photovoltaics (PV) has risen over the years due to its lower levelized cost of energy (LCOE) and the aim to decarbonize the energy supply. In South Korea, photovoltaic installations have gradually increased since 2000 due to supporting policies such as feed-in tariffs and Renewable Energy Standards. Photovoltaic installations reached 18,161 MW in 2021, with an average annual growth rate of about 70% from 2005 to 2021. South Korea announced that they aimed to have 20% of its power generation generated from photovoltaics by 2030. However, in 2021, renewable energy accounted for approximately only 4.7% of total electricity generation, with PV supplying 1%. This means that more effort is required in terms of installed capacity to achieve the country's target for energy supply from solar PV.

The rapid growth of global solar power has sparked concerns over how these panels will be managed once they reach their end-of-life (EoL). Considering the average life span for solar PV is 20 to 25 years, it is expected there will be more solar PV waste moving forward due to increased adoption of solar globally. The amount of waste solar modules generated in South Korea was 246 metric tons in 2019, 767 metric tons in 2020, and 735 metric tons in 2021. The amount of waste PV modules in 2023 is expected to be 998 tons.

The distribution of solar modules in their end-of-life methods of the modules are vague; while they are aggregated into mixed construction waste, and the majority of them are disposed in landfills or incinerated, the exact number for each method is difficult to estimate or track. Therefore, in 2023, the Korean government has implemented an Extended Producer Responsibility (EPR) for solar modules to ensure responsible waste disposal. Under the EPR, the mandatory target to recycle PV modules for 2023 is 159 tons. A penalisation has will apply for producers and distributors who fail to adhere to this requirement: producers pay 727 won (USD 6) per kilogram and distributors 94 won (USD 0.07) per kilogram. The government has also set a target for recycling/reusing waste modules at 80% of total waste by 2025. However, distributors and producers face challenges in meeting these targets due to a lack of management systems for waste modules.

Circular economy principles, where raw materials can be recycled and used again as resources for subsequent manufacturing can be implemented in this case. Solar cell materials from waste modules can be reused as valuable materials in the semiconductor industry in South Korea, which may benefit several industries as such materials are commonly imported. Therefore, it is necessary to predict the overall flow of waste modules and evaluate the environmental and economic impact according to the disposal method/technology.

Our study aims to assess the environmental impact of recycling or reusing waste c-Si solar modules through a life cycle assessment study that considers South Korea's national targets. The study also uses a cost-benefit analysis to estimate the economic impact from recycling the materials and the environmental avoidance costs resulting from the treatment of valuable waste materials, according to the different scenarios and waste management plans. Following this, possible alternatives that use resources from waste modules will be evaluated to achieve a circular economy in the production chain of PV modules.

Potential of BREEAM-C to Support Building Circularity Assessment

Monday, 3rd July - 12:21: Circular economy (short presentations) (A1.44 KOG)

***Dominique Wong* [1], *Chunbo Zhang* [2], *Francesco Di Maio* [3], *Mingming Hu* [1]**

***1.** Leiden University, CML, **2.** University College London, **3.** Technical University Delft*

This study analyses the potential of a framework of circular indicators put forward by the Building Research Establishment Environmental Assessment Method (BREEAM-C) as an answer to the prevailing need of a metric for building circularity assessment to promote circular construction.

Methods applied include literature review, cross-case analysis and collecting expert opinions using semi-structured interviews.

A careful scrutiny of the BREEAM-C indicators revealed that they are rooted in circular principles, realizable through circular strategies, and have given due consideration to circularity in different impact areas, structural layers and life-cycle stages of buildings. Moreover, BREEAM-C indicators not only show capacity in identifying CE-related practices implemented, but also serve as benchmarks testifying that CE principles/strategies are incorporated in the design, construction, operation and management of the buildings.

Water Circularity Indicator: Development and Application to a Pimpri-Chinchwad City in India

Monday, 3rd July - 12:28: Circular economy (short presentations) (A1.44 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Nikita Kakwani [1], ***Pradip Kalbar*** [1]

1. *Indian Institute of Technology Bombay, Mumbai*

The concept of Circular Economy (CE) in the water sector has gained traction in the research community, especially since the past decade. The prime reason for the increased attention is rapid depletion of available water resources coupled with water scarcity. Implementing CE strategies followed by monitoring has become crucial for achieving global and national water circularity targets. Several frameworks and indicators have been developed in this regard; however, no consensus has reached yet. In the present work, a novel **"Water Circularity Indicator (WCI)"** is developed to promote, assess, manage and improve the water circularity of a system. WCI is a modified form of Material Circularity Indicator (MCI) developed by Ellen McArthur Foundation and Granta design. Similar to MCI, WCI provides a value ranging from 0 to 1 where 0 indicates a linear water system and 1 indicates a circular water system. MCI is based on Reuse and Recycle strategies of CE, whereas WCI is inclusive of five strategies i.e. **Reduce, Reuse, Recycle, Reclaim and Restore**. WCI involves the evaluation of virgin water consumed inside the system boundary and total water going out of the system boundary to assess circularity. The ultimate goal is the urban water mass balance by **reducing virgin water consumption and wastewater generation** while increasing the water circulation inside the system boundary. WCI is then applied to Pimpri-Chinchwad city, one of the fastest-urbanizing cities in India. It is a major industrial centre of the country, accommodating major Indian automobile companies, pharmaceutical companies, small and medium enterprises, and many other national and multinational companies. The Pimpri-Chinchwad Municipal Corporation (PCMC) manages the city by providing infrastructural services to citizens. In this study, **WCI is evaluated for six scenarios** to assess and understand the water circulation potential of PCMC region and plan future interventions to promote circularity. Furthermore, the Government of India also promotes CE in the water sector and urban water balance through the ambitious Jal Jeevan Mission (Urban) (JJM(U)) by 2030. Hence, starting from the current scenario, i.e. for 2022 (Scenario 1) followed by 2030 and 2045 (Scenario 2 and 3) based on the water management plans by PCMC. Scenario 4 for 2030 as per JJM(U) targets. Two scenarios for 2030 and 2045 (Scenario 5 and 6), as recommended by authors considering the land-use and future growth by estimating the city's potential to reduce, reuse, recycle, reclaim or restore strategies. The results from the study indicate that the **WCI value will increase from 0.51 in Scenario 1 to 0.90 in Scenario 6**. Also, in the current scenario i.e. 2022, PCMC is providing around 535 MLD (Million Liters per Day) of virgin water and by 2045, PCMC will require around **300 MLD more water to cater to the demand**, which is beyond the capacity of available water sources. However, as per Scenario 6, the city only needs around 45 MLD more i.e. around 580 MLD, to cater to demand in 2045 by recirculation of around 350 MLD. **The municipality needs to rethink future infrastructure planning to move towards water circularity.** WCI provides an opportunity for utilities to monitor the status of the urban water cycle and improve the water flows by adopting CE strategies. Thus, the evaluation of WCI for a given system can provide valuable insights to decision-makers in achieving **urban water goals.**

Exploring the impact of a circular economy: A model-based analysis of steel and cement demand for buildings

Monday, 3rd July - 12:35: Circular economy (short presentations) (A1.44 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Meta Thurid Lotz [1], ***Andrea Herbst*** [1]

1. Fraunhofer Institute for System and Innovation Research ISI

Growing consumption levels and consequently increasing demands for goods and associated materials contrast the efforts currently undertaken to reduce greenhouse gas emission to mitigate climate change. A main contributor to the demand for the energy- and emission-intensive materials steel and cement is the building sector, which is currently responsible for about one quarter of steel demand and more than three quarters of cement demand in the European Union. On the one hand, this consumption could increase in future due to a rising demand for living spaces and service-related buildings. On the other hand, circular economy strategies, such as design for reuse, closed-loop recycling or material substitution could reduce this demand and contribute to achieving climate-neutrality. Accordingly, quantifying the impact of such measures is essential, in order to address and exploit the potentials systematically. We contribute to this by extending an existing material flow model with three exemplary circular economy actions: (1) Extending building lifetime through repair and renovation; (2) Using wood as main construction material instead of (reinforced) concrete; (3) Reusing prefabricated building elements. The modelling scope includes residential, commercial and public buildings in the European Union and United Kingdom. It differentiates building archetypes for three regions, five age cohorts and six building types. We modeled the stock, in- and outflows of steel and cement according to a predefined building stock development and consider circularity through three approaches: (1) Adapting the building stock development; (2) Adapting the building archetypes; (3) Introducing new flows into the model. We conducted a literature review to systematically identify potentials, limitations, preconditions and interactions of the circular economy actions and parameterized them to reflect the potential impact bandwidth compared to a reference scenario. The results show steel and cement reduction potentials of the individual circular economy actions. In particular, extending the service life of buildings and changing the main construction material can significantly reduce the prospective demand for steel and cement, but require adaptions of user and constructor behavior. In contrast, the reuse of building elements has a lower potential impact on the prospective material demand. However, the reduction potentials are characterized by uncertainty for various reasons, such as low technology readiness levels, necessary changes in the regulatory framework or behavioral trends and interaction with other transformation strategies. The presented approach enables the systematic comparison of such aspects for scenario analyses. This will be extended to further circular economy actions and validated through expert interviews. Consequently, this lays the foundation for comprehensive and consistent circular economy scenarios and the improved consideration in energy system analysis.

Computational methods (short presentations)

HESTIA: An open-access platform for sharing harmonised agri-environmental data

Monday, 3rd July - 12:00: Computational methods (short presentations) (B0.17 KOG)

Patrik Henriksson [1], ***Joseph Poore*** [2], ***Valentina Caldart*** [2], ***Guillaume Royer*** [2]

1. Stockholm University, 2. University of Oxford

Data with different formats and with different levels of transparency often obstruct reproducibility and hamper the collective knowledge of the LCA community. Choices related to methodology, emission models, and inventory data sourcing by individual LCA practitioners also render comparisons of LCIA results inaccurate. Nonetheless, a surge of publications aggregating non-harmonised LCIA data on food commodities have been published in the last decade, with the ambition to identify more sustainable diets. This has resulted in flawed conclusions based on differences in LCA models, rather than production practices. While harmonisation efforts, such as the PEF, can address some of these discrepancies, they will never be able to align all of the discrete sector-specific choices encountered in LCA modelling.

In response, we initiated HESTIA (hestia.earth) in 2019, an online open-access data platform that allows LCA practitioners and other users to upload LCI and LCIA data on agrifood systems using a standardised schema and glossary of terms. The LCI data can, in turn, be exported for integration in LCA software or be recalculated into LCIA results using our online calculation engine. This allows users to compare results across LCA studies using a harmonised set of terms, methodological choices, and assumptions, while being supported by gap-filling features to ensure comparable system boundaries and emission models.

HESTIA is already operational and is continuously being updated to make the platform more user-friendly and meet diverse requests from users. To date, 5,700 agricultural cycles are available on the platform, derived from published LCA articles and datasets from related sciences. We are now striving towards increasing individual contributions from the scientific community, both the LCA community and other agri-food related sciences. In return, users who upload data will be able to benchmark their products against a wide set of food commodities, using a harmonised approach. Users are also ensured more transparent archiving and interpretation of their data, thereby promoting dissemination of their work.

The presented research will demonstrate how we have streamlined the upload format to make it intuitive and accessible for a wide set of users. We will also share our ambitions to engage researchers from a diverse set of food-related sciences, NGOs, companies, and ultimately farmers with LCA through the HESTIA platform. Finally, we show examples of how HESTIA is and can be integrated by additional users using our API, including e.g. procurement processes, certification schemes, or data explorers.

Refining a Hybrid Input-Output Model Built on Process-Driven Physical Data for Bioenergy Footprinting

Monday, 3rd July - 12:07: Computational methods (short presentations) (B0.17 KOG)

Miriam Stevens [1], ***Shweta Singh*** [1]

1. *Purdue University*

Predicting structural changes to the physical and monetary economy from industrial-scale material reuse is one limitation to designing closed loop networks and understanding the full impacts of circular economy strategies on the environment. Trade or other survey data is often used for the purpose of creating hybrid IO models, if available, though production process models could also be used with the potential to more accurately characterize flows between industries and identify opportunities for substitution of inputs with suitable byproducts. This work leverages the integration of two cloud-based platforms for automated generation of economic and physical input-output tables, the US IELab and PIOT-Hub, respectively, to explore circularizing the flows between industries in a hybrid IO model for a small region of the United States. Physical data on the major biomass and industrial chemical flows associated with farming, fertilizer manufacturing, and biodiesel production are obtained from the PIOT-Hub; the PIOT-Hub employs mechanistic engineering models to generate PIOTs at any scale with reliable data validation and reproducibility. Data on the economic exchanges between sectors to support these industries are obtained from the US IELab, one of several national models in the Virtual Industrial Ecology Laboratory (IELab), which generates monetary IO tables at user-defined sectoral and regional aggregation levels. An impact analysis of biodiesel production using the hybrid IO model illustrates the difference in magnitude between the economic and environmental impacts of these industries. Further refinement of the approach to modelling a conventional versus circularized economic structure avoids inaccurate increases in upstream requirements when simulating waste reuse in the IO structure. We also address previous issues in reconciling estimated monetary value of PIOT transactions with subnational economic MIOT transactions encountered in the model's first implementation. This work demonstrates an application of the recently developed PIOT-Hub that could be suitable for either research into the material footprint of industrial networks, or to strengthen corporate environmental impact accounting and claims.

What are sustainable plastics? A review of interrelated problems and solutions.

Monday, 3rd July - 12:14: Computational methods (short presentations) (B0.17 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Sara Gonella [1], ***Vincent de Gooyert*** [1]

1. *Radboud University*

There is increasing attention to the sustainability issues related to plastics: greenhouse gases are released during their production and end-of-life management; millions of tonnes of plastics leak every year, causing environmental and health risks; when collected, plastics are often disposed of in landfills or incinerated; most recycled plastics are downcycled into a lower value product.

Conversely, plastics are affordable and versatile, and their use has been widely adopted in various sectors and industries. Plastics even have sustainability credit in some applications. For instance, food packaging is essential to our modern lifestyle and significantly reduces food spoilage. Alternative materials may not be as good at preserving food, may be less safe from a contamination point of view, may be more expensive, and may not necessarily be more sustainable.

The aim of this study is to provide a comprehensive overview of the sustainability problems associated with plastics and the solutions that are currently found in the literature. The study contributes to several discussions by showing how different problems and solutions are interconnected and influence each other, whereas they are usually analysed in isolation. As there is still no common definition of “sustainable plastic”, this study will check what this expression is associated with in the literature, e.g. a specific technology or concept.

The search is based on scientific review and overview articles and grey literature, such as reports from international organisations, NGOs and consultancy firms. The selected documents are coded using an open and axial coding approach. The aggregated variables are linked together by causal links, finally obtaining a qualitative System Dynamics model, following a procedure similar to that proposed by Eker & Zimmermann (2016) and Gürsan & de Gooyert (2021). The model highlights the feedback mechanisms that determine the (un-)sustainability of the system, the impacts that different interventions have on the plastics value chain, and the thematic areas that require further investigation to advance the transition towards sustainability.

Solutions discussed in the literature as potentially enabling a sustainable plastics transition range from bioplastics, recycling technologies, carbon capture and utilisation, banning single-use plastics, behavioural changes, etc. Most research to date has focused on technical solutions to one aspect of the problem; however, technologies do not operate in isolation, but are embedded in a complex socio-economic context. The widespread adoption of each solution would have different impacts and consequences on the plastics industry (new investments of different types and sizes might be required) and on the wider world system (e.g. large-scale production of bioplastics might have an impact on land use).

Alternative solutions could compete with each other for resources, funding and investment. Channelling a large amount of investment into one technology could create a new lock-in situation, which would make it difficult to switch (again) to a different, more sustainable technology, should it become available in a few decades. Taking effective measures against the unsustainability of the plastics system requires large-scale applications, but not all emerging technologies may have the potential to still be sustainable if brought to a large scale. It is therefore necessary to assess the impacts a new socio-technical system could have, to avoid causing undesirable side effects, perhaps even worse than those of the previous system. This study differs from many previous researches in its multidisciplinary and comprehensive approach to the topic of plastics and sustainability.

pacha: a python package for simulating agent-based models of socio-technical systems in sustainability research

Monday, 3rd July - 12:21: Computational methods (short presentations) (B0.17 KOG)

Gustavo Larrea-Gallegos [1], *Antonino Marvuglia* [1], *Tomás Navarrete Gutiérrez* [1], *Enrico Benetto* [1]

1. Luxembourg Institute of Science & Technology (LIST)

Global supply networks are now more complex and interconnected than ever, thus making it necessary to include aspects like complexity and human behaviour when proposing effective policies. For this purpose, agent-based modelling (ABM) has been commonly selected as the most suitable modelling paradigm, since it allows the inclusion of agency and the analysis of emergent behaviours. More specifically, sustainability inquires have relied on ad-hoc implementations of ABM that used different programming languages and frameworks when studying topics like incentives in agriculture, carbon taxes, green consciousness, or behaviour diffusion. The absence of general purpose, flexible and transparent tools for handling complexity-oriented research in industrial ecology causes a lack of replicability of studies in this field. We argue that this current limitation makes the potential of ABM to solve sustainability-related inquires still, to a large extent, untapped.

To deal with this issue, we propose **pacha**, an open-source software developed to allow the implementation and simulation of ABM models with focus on socio-technical systems and sustainability assessment. **pacha** has been fully implemented in python 3 as an installable package, and it is built on top of tools, notions and concepts proper to life-cycle assessment and complex adaptive systems. **pacha**'s core engine is composed by three main submodules: *builder*, *decisions,* and *simulation*. The *builder* submodule contains all the tools that allow the construction of producer and consumer agents, whether they are defined by the user (i.e., spreadsheets, jupyter notebooks) or adapted from existing databases (e.g., ecoinvent). This module relies on a mathematical framework that represents agent's *operational configuration* as a set of matrices and vectors with algebraic properties. The *decisions* submodule contains the most basic actions and decisions that agents can perform (e.g., buy, sell, request quote, produce, etc) which, in addition to the *operational configuration,* constitute the basic elements of the agent's *Beliefs, Desires, and Intentions* architecture. Finally, the *simulation* module provides the required tools to build a simulation environment in which the agents are connected in a production-consumption graph, whether it is arbitrarily designed or by using common network topologies. The simulation environment can handle stochasticity in terms of agent's properties and initial conditions which can be explicitly defined by the user when setting scenarios. Moreover, **pacha** is capable of recording flows of information, money and physical elements (i.e., products and emissions) at every simulation step and for every agent, meaning that impacts can be analysed at an entity or at a system level. Using any text editor or Integrated Development Environment, rules and case-specific scenarios can be ingested as user-made functions built on top of the decisions and actions provided by the *decisions* module.

We present **pacha**'s capabilities in a proof-of-concept in which we evaluated the consequences of introducing sustainability-driven agents (i.e., Agents of Change (AOCs)) in a conventional profit-driven production and consumption network. To test the package, we studied the reduction of emissions and the likelihood of survival of AOCs in a series of experiments. Our results indicate that the introduction of AOCs can lead to a reduction of environmental impacts that is more pronounced when the AOCs appear in the tier closer to the consumer side. Finally, we demonstrate that **pacha** is flexible enough to consider different industries and types of agents to conduct research related with complexity-driven sustainability inquires.

THE INVESTMENT GAP IN THE INDUSTRIAL SECTOR: THE CASE OF THE CHLORINE CLUSTER IN THE PORT OF ROTTERDAM

Monday, 3rd July - 12:28: Computational methods (short presentations) (B0.17 KOG)

laurens oei [1], ***Yasin Sagdur*** [1], ***Emile Chappin*** [2], ***Dimitrios Xevgenos*** [3]

1. Water & Energy Intelligence BV, 2. TU Delft, 3. Delft University of Technology

Sustainable technology investments in energy efficiency measures, renewable energy production and recirculation of waste streams are currently not being made in the industrial sector, even though the economics seem favourable (Grubb, 2014), (Hartley, Roosendal & Kirchherr, 2022). According to Gerarden, Newell & Stavins (2017) numerous 'barriers' hamper the investments in sustainable technologies and they mention two broad categories: market barriers and behavioral barriers. Although they conclude that these two categories are theoretically sound, there is currently only limited understanding on how the barriers should be understood, how important they are in various contexts, and how they should be addressed.
To research the effect of market and behavioral barriers on investments in the industrial sector, this paper used the Port of Rotterdam (PoR) chlorine cluster as a case. The PoR chlorine cluster is highly interconnected and energy-intensive industrial cluster located in the Botlek/Pernis area. This case was chosen because of the following arguments:

- Investment gap is also noticed at the PoR chlorine cluster
- Following the suggestion for future research from Scherpbier (2018)
- Public availability of techno-economic data for the PoR chlorine cluster

Next, the research approach comprised of a literature review on current investment decision making and currently used quantitative support models. Followed by a model study that examined how market & behavioral barriers affect the sustainable technology adoption at the PoR chlorine cluster. From the literature review on the following points were concluded:

- For the investors the main question is how to most effectively allocate investment capital to transition from fossil fuel based technologies towards renewable or less polluting technologies.
- Quantitative decision support models play a pivotal role in decision making processes
- Almost all of the currently used decision support models are normative optimization models.
- Normative optimization models do not incorporate both market & behavioral barriers and do not allow for the simulation of various contexts.

Therefore, this research expanded current optimization models with the inclusion of market & behavioral barriers and allow for the simulation various contexts. This resulted in a linear optimization model. The model represents the PoR chlorine cluster on a highl-level, makes it possible to explicitly model the technology stock and simulate decarbonization pathways between 2022 and 2050. The incorporation of the barriers in the model resulted in a range of investment types, some of them non-optimal and varying in perspectives on valuing the future. Next, the model was used to simulate the chlorine cluster's investment decisions under varying configurations of exogenous uncertainties in the form of policy, energy and technology prices. These varying configurations of investment types and exogenous uncertainties were in turn compared to a normative baseline benchmark. This resulted in the following key findings:

- The market & behavioural barriers lead to postponed sustainable technology adoption between 2022 and 2050, compared to the normative baseline benchmark.

- Additionally, the barriers explain the existence of the investment gap in case of the PoR chlorine cluster.

To conclude, the results suggest that the commonly used optimization models overestimate the adoption of sustainable technology, by not incorporating market & behavioral barriers. Therefore decision makers in the industrial sector should be made aware of it's importance and be persuaded to add them to their currently used quantitative support methods.

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Consumption, Policy, and Products (short presentations)

Gone too soon: A socio-economic analysis of product repair practices in Pakistan

Monday, 3rd July - 12:00: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Hina Habib [1], ***Jo Dewulf*** [1]
1. *Ghent University*

Product repairs play a vital role in promoting sustainability and preserving the environment. It is a responsible and cost-effective way of extending the lifespan of products and reducing the demand for new ones.
This study aims to investigate the relationship between consumer purchasing power (lower, middle and upper-middle urban population) and product repairs. A survey was conducted in Lahore, Pakistan to gather information about the in-use lifetime of cooling and freezing appliances (fridges (incl. combi-fridges), freezers, and air conditioners), their common faults, repair frequency, and associated costs (including the spare part and technician fee). A shared belief behind product repair is value for money and responsibility in spending. By gathering data from a diverse range of respondents, a comprehensive analysis of repair practices across different socio-economic backgrounds was facilitated. The preliminary results suggest that individuals with lower incomes are more likely to repair their electronic devices multiple times rather than replace them, while those with higher incomes are more likely to choose new devices if they malfunction. Factors such as cost considerations, perceived convenience, and effort (in terms of time) play a role in these differences. Availability of spare parts for common faults and trust in technician expertise are also significant factors in the repair culture. Repair prices for cooling and freezing appliances range from 5 to 40 euros.
In conclusion, understanding the socio-economic factors that influence repair culture is critical in promoting sustainable consumption patterns. By repairing products, we can reduce waste, conserve resources, and maintain the value of the items we own.

What do people think is good for the environment, and how does LCA-based information influence that perception?

Monday, 3rd July - 12:07: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

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People's awareness of decarbonization is growing, but it is not linked to scientific knowledge. Although LCA can provide quantitative information on the environmental impact associated with people's daily activities and consumption, there seems to be a large gap between the knowledge obtained from LCA and people's perceptions. In this study, we aimed to clarify what people perceive to be good for the environment in their daily activities, and how their perceptions are affected by the provision of scientific information. In order to respond to this research purpose, we conducted two surveys (Surveys I & II) in this research.
In Survey I, respondents were asked what things and actions they think a) good, b) bad, and c) uncertain for the environment in six areas: transportation, clothing, food and eating, product selection and shopping, waste disposal, and other household activities. The respondents were asked, in an open-ended manner, to list three each for a) to c) in each area. The respondents were also asked about their socio-demographics, habits, and personal characteristics. At the end of the questionnaire, they were asked about free opinions about the environmental issues. The online survey was conducted in November 2022, targeting people in their teens to over 70s across Japan, and 6,580 samples were gained. Their cognitive responses were analyzed by extracting words and analyzing them based on their frequency. The responses to the personal characteristics were subjected to factor analysis to extract common factors and analyzed using factor scores.
As a result of Survey I, it was found that 440 out of 6,580 people recognized that "local production for local consumption" was good for the environment in "food and eating" and "product selection and shopping" areas. Based on this, we picked up "local production for local consumption" as a case study, and tried to evaluate the effect of LCA-based information provision.
For Survey II, we made three types of information based on Hospido et al.(2009). They showed LCA results for three cases of lettuce consumed in the UK: i) outdoor grown, ii) greenhouse grown, and iii) outdoor grown in Spain and imported. We divided respondents into three groups (G1 – G3) to assess the effect of different information provision. All the three cases (i, ii, and iii) were shown for G1, while two of the three cases were picked up and shown to highlight the environmental impacts of transportation and greenhouse cultivation, respectively, for G2 (i and iii) and G3 (i and ii). In all the cases, the data were shown in color bar graphs, and simple illustrations and brief explanations were included to facilitate understanding of the graphs. Before providing the information, the respondents were asked whether and why they believe that local production for local consumption is better for the environment. After being provided with the information described above, respondents were asked what they thought of the description and content of the information. The online survey was conducted in January 2023 of the respondents who responded to Survey I, resulting in a sample of 4,204.
The groups exposed to partial information (G2 and G3) tended to be unconvinced by the information, whereas the group exposed to full information (G1) were 'surprised' by the information and more likely to change their initial perceptions of local production for local consumption.

Product obsolescence: relationships with product lifetime, product type, and household characteristics

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:14: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Haruhisa Yamamoto [1], ***Masahiro Oguchi*** [1], ***Daisuke Nishijima*** [2], ***Shinsuke Murakami*** [3]

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Premature product obsolescence is a major barrier to product lifetime extension and, ultimately, to a circular economy. A detailed understanding of the current situation of product obsolescence and its potential factors is essential; therefore, two distinct empirical studies regarding electrical and electronic equipment (EEE) were conducted. The first study investigated the differences of the lifetimes of EEE across different obsolescence reasons, specifically product failure and relative obsolescence (consumers' decisions to stop using their products before failure), based on a self-administered consumer questionnaire survey in Japan. We also compared the influential obsolescence reasons between different product types, namely up-to-date products (products are often updated due to the changes in their looks or technology) and workhorse products (products of which functional utility is valued). The results indicated that failure was the dominant obsolescence reason for PCs and microwaves. However, for microwaves, the representative workhorse products, obsolescence due to relative obsolescence was more likely to shorten the lifetime than that due to failure. Furthermore, relative obsolescence, most notably functional obsolescence, was found to be as influential as failure for all years of use in the case of digital cameras, which are representative up-to-date products, indicating that the process of product obsolescence differs depending on the product type. The second study analyzed the relationship between obsolescence reasons and household characteristics, including household income and residence type. Datasets from a Japanese official statistics survey on five types of EEE were utilized. We found that functional obsolescence was more prevalent among higher-income households, especially for mobile phones, which also represent up-to-date products. In addition, households living in rent house or headed by persons aged under 50 years old were very likely to stop using refrigerators, air conditioners, or vacuum cleaners after moving out of the house, and the lifetime of those devices was significantly shorter than that of devices replaced due to other obsolescence reasons. Based on these results, effective measures to prevent product obsolescence are discussed by obsolescence reason and product type.

Using agent-based modeling to explore aquaponics

Monday, 3rd July - 12:21: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Marissa Breitenstein [1], ***Elisabeth Bautista*** [1], ***Andrea Hicks*** [1]

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Food security has been and will continue to be fickle for many regions around the globe, especially as human population continues to grow. Aquaponics, as a more sustainable food production system, has been suggested as a typical operation produces high protein fish and nutritious fruits and vegetables, while also mitigating much of the waste streams produced by more traditional methods, such as aquaculture and hydroponics. Aquaponics returns food production back to more natural mechanisms in regard to nutrient and water cycling, furthering the idea of industrial ecology by recognizing the balance between the need for mass and sustainable food production. As aquaponics is further optimized, educational outreach for the new technology is necessary to educate the public on the food production method. Agent-based modeling is a visual and interactive approach to educating the public on aquaponics. Utilizing agent-based modeling as an educational tool for teaching aquaponics allows the user to interact with and understand the basic mechanisms behind the food production method while also visualizing the greenhouse gas emissions produced by the system over time. Developing and utilizing the model in outreach events will allow for data collection on the effectiveness of the educational methods to better inform future research to education methodologies.

How does China's emerging middle-income group reshape consumption patterns and carbon footprint?

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:28: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Xinzhu Zheng [1]

1. *China University of Petroleum - Beijing*

The lifestyle changes of China's emerging middle-income group have raised severe concerns about growing carbon emissions while stimulating consumption. Converting the qualitative concerns to quantitative understanding and guiding the group to low-carbon lifestyles rather than copying the carbon-intensive ones of the rich is critical for achieving the goal of common prosperity and carbon neutrality simultaneously. This study performs the quantitative assessment by combining machine learning, input-output model, and household survey data and compares the carbon emission impacts of various income-increasing paths and their policy mix. The results show that if the scale of the middle-income group doubles during 2018-2030 (i.e., a 24% increase in the share of the national population with an annual income of RMB 33,000-80,000 at constant 2018 prices), the consumption upgrade of the emerging middle-income groups would bring an additional carbon emission of 0.48-0.60 billion tons in 2030. Compared to the business-as-usual scenario, the mitigation rate needs to increase by 9.5-11.9% to offset the emission increase. Second, in the case that only the impacts of income increase are considered, the emerging middle-income group's carbon emissions are significantly lower than those of the original middle-income group (0.2-0.4t difference at the per-capita level). The gaps can be explained by the contributions of other factors (e.g., socioeconomic characteristics, consumer psychology, behavioral habits, etc.) and imply the mitigation potentials in climbing the income ladder. Third, urbanization brings more marginal carbon emission impacts than human capital enhancement and social security system improvement. The mix of these policies shows synergetic or counter-productive effects depending on the policy implementation context.

Sustainable consumption – moving from niche to mainstream

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:35: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Göran Finnveden [1], ***Karin Bradley*** [1], ***Mikael Klintman*** [2], ***Jörgen Larsson*** [3], ***Matthias Lehner*** [2], ***Oksana Mont*** [2], ***Jonas Nässén*** [3], ***Åsa Svenfelt*** [4]

1. KTH, 2. Lund University, 3. Chalmers University of Technology, 4. Linköping University

"Mistra Sustainable Consumption – from niche to mainstream" is a Swedish eight-year research program aiming to provide a knowledge base that stimulates a transition to more sustainable consumption. The goal is to contribute with knowledge on how sustainable consumption that is currently practised by a few can be scaled up and become more common. The program is interdisciplinary and transdisciplinary and collaborates with societal partners from businesses, governmental agencies, municipalities, regions and NGOs. There is a focus on food, holiday travels and homemaking, but other consumption areas are also considered. The research explores the roles, strategies and practices of policymakers, businesses, NGOs and individuals. The program is currently more than halfway, and this paper aims to present examples of key results so far and outline planned studies.

Our scenario studies conducted in the program in collaboration with others have shown that a combination of technological and behavioural changes is necessary to reduce consumption-based emissions of greenhouse gases (GHG) by 90 % until the year 2050. Only technological changes that improve efficiency or behavioural changes would not be enough. One study demonstrated that the total GHG emissions from private consumption could be reduced by almost 40 % through currently available alternatives in three areas (food, holiday travel and furniture). On the one hand, it is significant that already today, without large investments or developments, GHG emissions from households, can be nearly halved. On the other hand, these levels are still far from being sustainable. More fundamental changes are also needed, such as strategies for sufficiency. One study tested a voluntary reduction of working hours in Sweden with a corresponding salary decrease. This increased well-being among both higher and lower-income groups and could also lead to decreased environmental impacts. Among the drawbacks was increased economic insecurity for some participants. New business models could also support a transition to more sustainable consumption. Some companies are testing models based on leasing, renting etc that could be more sustainable. These models are becoming accepted primarily for social and functional values rather than environmental reasons. New policy instruments are needed for more sustainable consumption. In the research program, many promising policy instruments in food, aviation and consumer durables have been identified and analysed. Public acceptance of sustainable consumption policies has been identified as a critical factor. To improve public acceptance of policies, fairness, effectiveness and targeting companies have been identified as keys. Synergies between different sustainability goals are also important for policy acceptance. Our research shows that significant health benefits and GHG reductions can be achieved if half of the current consumption of red and processed meat is replaced with vegetables and legumes. When developing policies, rebound effects are important to consider. However, our latest publications demonstrate that more climate-friendly behaviour of environmentally committed consumers in one area (not flying, not owning a car, having a vegan diet or not living in a detached house) does not increase emissions in other areas. This finding goes against previous studies reported in the literature, and points to the need to further investigate how, and why, the rebound effect varies in different sectors and problem areas of consumption. See www.sustainableconsumption.se for publications from the program.

Critical Raw Materials 1 (short presentations)

Lithium-Sulfur Technology Reduces the Environmental Impact of Lithium-Ion Batteries

Monday, 3rd July - 12:00: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Heng Yi Teah [1], ***Qi Zhang*** [1], ***Kotaro Yasui*** [1], ***Suguru Noda*** [1]

1. *Waseda University*

Lithium-sulfur (Li-S) batteries are expected to be the next-generation lithium-ion batteries by 2050. They exhibit useful properties like high theoretical energy density (2,510 Wh/$kg_{Li\text{-}S}$ vs. 500 Wh/$kg_{NCM\text{-}graphite}$) and an opportunity to replace cobalt and other critical materials, in which sulfur is a petrochemical industry byproduct and an abundance nature resource.

This study aimed to investigate the environmental performance of a new carbon nanotubes (CNT)-based Li-S battery architecture. The CNT acts as binders, conductive fillers, and current collectors; therefore, can reduce battery materials and simplify manufacturing processes. We conducted a process-based life cycle assessment (LCA) to identify the anticipated reduction of environmental impacts in contrast to conventional practices.

First, we designed a battery pack for electric vehicles based on our lab-scale coin cell experiment. We applied BatPaC model to estimate the materials requirement for the expected pouch cells. Then, we performed a cradle-to-gate LCA to evaluate the environmental performance of the Li-S battery. We defined the functional unit as 1 kWh Li-S battery normalized from a 100-kWh battery pack. We modelled the global warming potential impact (GWP100, IPCC2013) on openLCA platform supplemented by the background data from Ecoinvent v3.8.

To support the Li-S technology, we examined three scenarios that were critical to improving the environmental hotspots. We examined the effect of self-supporting CNT matrix in reducing the size of aluminum and copper current collectors in S1. We examined the effect of improving anode material efficiency to reduce lithium in S2. Finally, we examined the effect of reducing DME solvent through increasing the concentration of polysulfide solution for positive electrode production in S3.

Our assessment showed that the proposed Li-S cells were associated with 105 kg-CO2e per kWh (capacity) in the benchmark. The contributors in descending order were anode production, cathode production, process energy during cell manufacture (including dry room), current collectors, and others. Considering the technology improvements, S1, S2, and S3 resulted in 18, 5, and 4 kg-CO2e per kWh reduction, respectively. S1 showed that the effect of reduction of current collectors to 1/10 of size was significant although the CNT production was carbon intensive. S2 showed some improvements based on a target N/P ratio but lithium was still a carbon-intensive material. S3 showed that experimenting with less DME solvent for the catholyte was necessary to reduce the impact on cathode.

Another significant finding was the drying process during the cathode production process. Conventional direct drying requires more heat, supplied by electricity or steam, for solvent evaporation, which is an environmental hotspot. Our approach applies an additional filtration step before the evaporation. This enables the reuse of more than 99% of solvent, and more importantly, reduces the remaining solvent, thus lowering the heating energy significantly.

In comparison to a reported Li-S battery, which applied a graphene-oxide sulfur cathode, our proposed Li-S architecture could reduce up to 43% global warming potential, showing a promising alternative. However, there were some limitations in this study. We have calculated energy use of dry room based on cell mass due to lack of reliable data, while the actual electricity use is related to the usage time in the facility. The Li-S battery has a short cycle life (~100 cycle) due to lithium dendrite growth issue at current development; the cycle life was not considered.

How Do Critical Materials Impact the Carbon-neutral and Fossil-free European Energy System?

Monday, 3rd July - 12:07: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

Fei Wu [1], ***Francesco Lombardi*** [2], ***Christian Moretti*** [1], ***Adrien Mellot*** [1], ***Jaco Quist*** [2], ***Stefan Pfenninger*** [2]

***1.** ETH Zurich*, ***2.** TU Delft*

There are many options for designing a carbon-neutral and fossil-free European energy system. In recent work, we showed up to hundreds of radically different sector-coupled system designs that all allow for attaining such a goal at a similar cost[1]. However, substantial differences in the embodied critical raw materials may exist among system designs that otherwise appear equivalent from a techno-economic perspective. Given the growing concerns about the feasibility and impact of critical materials supply in support of the energy transition, it is imperative to quantify to what extent such trade-offs among feasible system designs exist.
With this study, we aim to do so by soft-linking energy system modeling and life-cycle assessment modeling within an original computational workflow. Building on the hundreds of techno-economically feasible system designs generated with the Euro-Calliope energy system model in our previous work, we integrate those with life cycle inventories on the associated critical materials consumption. We apply the novel workflow to quantify the impact of critical material supply on the energy system design space for a carbon-neutral Europe.
Our findings confirm that marginally different energy system designs may require significantly different amounts of critical raw materials, some of which are more likely to conflict with supply-chain bottlenecks. Nonetheless, by examining future circular economy practices, we show that the improved circularity in raw materials supply chains may help mitigate the resulting reduction of the energy system design space. Moreover, we identify those energy technologies for which circularity would be most impactful from a system perspective. Our findings can assist policymakers in formulating more realistic, sustainable, and comprehensive energy policies in synergy with circular economy efforts

References:

1. Pickering, B., Lombardi, F. & Pfenninger, S. Diversity of options to eliminate fossil fuels and reach carbon neutrality across the entire European energy system. Joule 6, 1253–1276 (2022).

Quantitative assessment of global future Lithium supply: Simulating mining projects and predicting production start times

Monday, 3rd July - 12:14: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

Laura Buarque Andrade [1]***, Max Frenzel*** [1]***, Britta Bookhagen*** [2]***, Carolin Kresse*** [2]

1. *Helmholtz-Zentrum Dresden-Rossendorf, Helmholtz Institute Freiberg for Resource Technology, Freiberg,* ***2.*** *Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)*

Whether primary lithium (Li) sources will be able to supply the rapidly growing needs of the electric mobility transition has recently caused considerable controversy. Existing assessments need to be improved by a lack of consideration for the decision-making processes occurring at the level of individual mining projects. In the present contribution, we demonstrate how these processes and associated uncertainties can be incorporated into an assessment of the likely future evolution of the global Li market. Our method uses Monte Carlo simulations to achieve this goal. A global database of existing Li mining projects (all development stages, including case histories) is used to build models to estimate the likelihood of each project proceeding to the next development stage in any given year, depending on specific project characteristics such as location, deposit type, and ore grade, as well as market conditions, i.e., Li price and demand. Iterative stochastic simulations are then run, in which projects are moved through the development pipeline according to these estimated likelihoods, year-by-year, up to 2050. Discoveries are also included in the model to achieve realistic results over the relatively long period covered. Simple, functional models estimate future Li demand, including uncertainty. The simulations generate a large set of equally probable scenarios (1,000 or more) of which projects enter production when, whether primary supply can meet demand in any given year, and what the likely mean Li price is for that year. Summarising the data from all scenarios provides an impression of the likely evolution of the Li market up to 2050. Besides this likely market evolution, the simulation outputs can be used further to assess the probable environmental impacts of future primary Li supply

Environmental potential of circular lithium-ion battery production from an overall European market perspective

Monday, 3rd July - 12:21: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

Raphael Ginster [1], Steffen Blömeke [1], Jan-Linus Popien [1], Jana Husmann [1], Christian Scheller [1], Felipe Cerdas [1], Christoph Herrmann [1], Thomas S. Spengler [1]

1. Technische Universität Braunschweig

The European passenger car sector is transforming towards battery electric vehicles to reduce CO_2e emissions and meet climate targets. However, necessary batteries require limited valuable raw materials, and battery production accounts for a significant share of the battery electric vehicles' life-cycle CO_2e emissions (Koroma et al. 2022). Therefore, policies in the upcoming EU Battery Directive force the usage of recycled materials from spent batteries in new batteries by establishing circular production and limiting resulting CO_2e emissions.
Recent studies forecast the end-of-life market of electric vehicles and the resulting recycled material quantities (Bobba et al. 2019, Baars et al. 2021, Neidhardt et al. 2022, Shafique et al. 2022, Zeng et al. 2022). Thereby, mainly global vehicle and material flows are assessed without considering spatial differences between EU countries. These models focus mainly on NMC battery chemistries, although the LFP battery chemistries market share is expected to increase (IEA 2022). Moreover, the underlying implementation for battery production and recycling processes as "black-box models" prevents process- and material-specific (recycling) efficiencies. In contrast, Life Cycle Assessment studies consider detailed descriptions of underlying processes for specific battery production and recycling routes but missing an overall market perspective over time (Blömeke et al. 2022, Kallitsis et al. 2022, von Drachenfels et al. 2022). As shown by (Ciez and Whitacre 2019) and (Mohr et al. 2020) advantages of using recycled materials in battery production depend on the specific cell chemistry, the processes used during recycling, and the investigated impact category. The sole consideration of these individual aspects may lead to inaccurate estimations of recycled material flows, environmental impacts, and derived actions. As a result, integrated approaches evolved to model market behavior and to perform Life Cycle Assessments for selected battery materials (Ambrose and Kendall 2020a, Ambrose and Kendall 2020b, Cusenza et al. 2019). Hence, integrating different assessment models is necessary to analyze the potential of European circular battery production from an environmental view.
Here, we evaluate and discuss the European circular battery production's potential on environmental impacts by utilizing an integrated assessment model. Our approach combines country-specific vehicle market models based on a system dynamics approach with detailed battery production and recycling Life Cycle Inventories to quantify material flows and stocks over time. To address the system's inherent deep uncertainty, we use an open exploration methodology to report estimated environmental impacts and quantify the probabilities of their occurrence (Kwakkel 2017, Marchau et al. 2019). The country-specific market models of the EU countries forecast the necessary new and available spent batteries until 2050, differentiated by battery capacity and cell chemistry. Based on these quantities, available recycling technologies are used to quantify the material-specific recycling material flows. Afterward, the utilization rate of the produced recycling materials in new batteries is calculated. During simulation, environmental impacts are calculated over time using the linked Life Cycle Inventories for battery production and recycling combined with the respective characterization factors. The assessment of different scenarios within the open exploration framework supports future policy decisions and the identification of critical system components throughout the transition toward a circular battery production.
In summary, our approach and results enable the review of the current legislation regarding their ambitions and feasibility, and evaluate the environmental impacts of primary and recycled material shares in circular battery production from an overall European market perspective.

Trends in technological readiness, critical raw material use, and electricity consumption of water electrolysis technologies up to the year 2050 – prospective technological and environmental assessment

Monday, 3rd July - 12:28: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

***Jan Christian Koj* [1], *Petra Zapp* [1]**

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Water electrolysis technologies to produce green hydrogen are discussed as a promising option for the decarbonization, diversification and security of supply of future energy systems. In the recent past, technological maturity of water electrolysis technologies has increased. Despite this progress, further technological improvements are expected in the long term. This study examines the trends in technology readiness, critical raw material use and electricity consumption of the three most mature water electrolysis technologies, polymer electrolyte membrane, alkaline, and solid oxide electrolysis cells, up to the year 2050. To date, there is a limited number of prospective Life Cycle Assessment (LCA) studies that consider all three technology options. In addition, changes in projected material requirements for electrolysis construction in general and potentially critical raw materials in particular are rarely used in existing LCA studies. Using LCA and trend extrapolation, this study provides new insights into the potential reduction in environmental impacts by technological improvements in electrolysis technologies. Historical, current, and projected data from the scientific literature are used to extrapolate these parameters. For critical raw materials and electricity consumption, trends are assessed using exponential trend curves. The assessment of the projected technology readiness shows that all three electrolysis technologies are expected to reach the highest level of technological maturity already in 2030. Regarding the demand for critical raw materials, there is data available in literature, especially for iridium, platinum, and titanium. The literature-based trend extrapolation suggests that demand for these materials could fall by more than 55% between 2020 and 2030. By 2050, the use of various critical raw materials is expected to decrease by more than 90% compared to today. The reductions in electricity demand for electrolysis technologies are much lower due to their physical limitations. Depending on the technology, the reduction in electricity demand between 2020 and 2050 ranges from 6 to 17%. Considering the impact of these changes on the environmental impact of hydrogen produced by wind power (green hydrogen), further reductions in the global warming potential of more than 20% are possible by 2050. With shares up to 90% the electricity demand clearly dominates the contributions to the global warming potential of hydrogen production in the years 2020 and 2050. The knowledge gained from the detailed technological and environmental assessment of the water electrolysis technologies and the insights into their future development can also be used as a starting point for criticality analyses and sustainability assessments.

Urban mining future of copper under the low-carbon transition of China's power sector

Monday, 3rd July - 12:35: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

Min Hao [1], ***Peng Wang*** [2], ***Wei-Qiang Chen*** [3]

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To achieve carbon neutrality by 2060, China must urgently build a new power system using new energy resources. The construction of a new power system requires an adequate supply of critical metals, and copper occupies a pivotal role. The copper reserves in China are insufficient, the grades are low, and imports are crucial. Therefore, the following three areas will be researched:

Firstly, material flow analysis method will be used to build the material metabolism model database of copper from 1950 to 2020. It is found that the consumption of copper resources in China has been growing rapidly, but the reserves of local resources are extremely scarce. Therefore, China's copper supply is highly dependent on the import of resources and exhibits a trade pattern of "both ends in and middle-out," namely, the primary production end and the recovery end are net imports while copper products processing and manufacturing in the middle are net exports. The social reserve of copper resources in urban mining fits an exponential growth model. Copper in-use stocks in China were 100-110 million tons in 2020, which exceed China's copper ore reserves and can become the main source to meet China's future copper demand. Therefore, the development of copper resources for urban mining is crucial for reducing the dependence of copper on foreign countries and ensuring the sufficient supply of domestic copper resources.

Second, according to the regular pattern of historical evolution, this project integrates material flow analysis and scenario analysis methods, selects the power system structure in Integrated Policy Assessment Model of China (IPAC), constructs China's power system copper resource cycle trade coupling quantitative model, and further explores the evolution trend of China's copper resource cycle under different scenarios in 2060, especially under the carbon neutralization scenario.

Finally, the corresponding recovery scenarios and trade scenarios for copper are used to formulate the resource management path. The results of this project will be accurately, intuitively, and dynamically described as different low-carbon energy scenarios, especially the demand, supply and domestic circulation mechanism of copper resources under the goal of achieving carbon neutralization in China. The research results of this project will provide guarantee for reducing the supply risk of China's copper resources, provide strategies for getting rid of the situation of dependence on copper resources import, provide theoretical support for the sustainable development of copper industry and other related resource policies, and provide methodological reference for the future supply and demand and recycling research of other metal resources.

IE and Industry (short presentations)

Net-zero transition in the cement industry: a case study of China based on plant-level data

Monday, 3rd July - 12:00: IE and Industry (short presentations) (B0.31 KOG)

***Xinke Song* [1], *Can Wang* [1], *Gang Liu* [2]**

***1.** School of environment, Tsinghua University, **2.** SDU Life Cycle Engineering, Department of Green Technology, University of Southern Denmark*

The cement industry is one of the most hard-to-abate sectors and is a priority sector for carbon control. Previous studies on the decarbonization transition in the cement industry have rarely carried out the spatial-geographic analysis of decarbonization technologies, and this study filled this gap. This study constructed a plant-level technology optimization model that considers the uncertainty of future socio-economic development and combined plant-level heterogeneity data with spatial attributes on the supply side to calculate the low-carbon technology deployment path for each cement plant to achieve the carbon neutrality target. This study took the cement industry in China as a case study. Through the simulation of cement demand under SSPs and the analysis of an optimization model for 1620 cement plants, we found that: a transition cost of RMB 2.4 trillion is required to achieve the carbon neutrality target by 2060 from the present to 2060 under the baseline scenario; cement plants in the east and west are more suitable for deployment of the carbon capture and storage (CCS)/direct air capture (DAC) technologies due to factors such as the potential for storage sites and climatic conditions. This study generated marginal abatement cost curves for 17 decarbonization technologies for the cement industry, with energy efficiency improvements being the lowest-cost technology option but with limited abatement potential and DAC being the highest-cost technology option but with the greatest abatement potential. This study provided a reference for designing a deep decarbonization pathway for the cement industry under a zero-carbon vision.

The Industrial Ecology Approach to Bioeconomy Monitorng

Monday, 3rd July - 12:07: IE and Industry (short presentations) (B0.31 KOG)

Hanna Helander [1]***, Christian Lutz*** [2]***, Martin Distelkamp*** [2]***, Rüdiger Schaldach*** [1]***, Meghan Beck-O'Brien*** [1]***, Stefan Bringezu*** [1]

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That industrial ecology can offer important insights for a transformation towards a more sustainable socio-ecological system is broadly recognized. Yet, how industrial ecology research effectively enters the political sphere is a topical discussion in the community. One way is to address political initiatives such as the *bioeconomy* and engage in the monitoring of such concepts. The widely promoted bioeconomy bears the risk of overexploiting lands in the eagerness of substituting fossil-based materials and energy sources. Dominating monitoring systems for political concepts, including the bioeconomy, depart from the specific political goals, on which basis a set of indicators related to each goal are selected. However, to identify trade-offs and crucial system interactions, a system perspective addressing the socioeconomic metabolism needs to be more prominent. In the case of the bioeconomy, this includes for instance the competition of lands for different purposes. We see a pressing need to bring the socioeconomic metabolism perspective more prominently into political concepts. In this study, we aim to explore how this can be realized in the context of the bioeconomy. Specifically, it aims to (1) disclose some essential requirements for a bioeconomy monitoring system based on a socioeconomic metabolism perspective to be relevant for policymakers, and (2) delineate a modeling and monitoring structure that, to a great extent, meets the identified requirements.

Our analysis integrates two main perspectives. First, we investigate the requirements related to political relevance. This includes the ability to link outcomes to political goals, topical discourses, and political processes as well as to provide effective communication. Second, we outline some key environmental and resource issues related to the bioeconomy concept. The latter departs from a socioeconomic metabolism perspective while identifying crucial impacts in the ecological sphere. Next to these perspectives, we recognize the need for pragmatism for effective implementation and use, including the availability and robustness of data and methods, which adds some frame conditions to our proposed modeling and monitoring structure.

This analysis and proposed monitoring structure will help bridge the political concept of bioeconomy and the crucial system perspective provided by industrial ecology approaches. We believe that it also provides an example of how to integrate and strengthen the industrial ecology perspective in political concepts beyond the bioeconomy, as our analytical approach can serve this purpose also in other contexts.

Net-zero transition of the chemical industry: framework and results

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:14: IE and Industry (short presentations) (B0.31 KOG)

Amrita Sen [1], Vyom Thakker [1], George Stephanopoulos [2], Bhavik Bakshi [1]

1. The Ohio State University, 2. The Global Kaiteki Center, Arizona State University

The anthropogenic emission of greenhouse gases to the environment must be reduced to net-zero if the ill-effects of climate change are to be contained. The commitments of industries and governments to this transition, while well-meaning, are often unsubstantiated by tangible strategies.

The chemicals and materials industry (CMI), though hard to decarbonize, is the key to net-zero transitions for other sectors. Thus, establishing net-negative emissions for the global CMI is critical. An array of technologies is being employed to enable this transition. However, in the absence of rigorous methods for evaluation and design, the path to net-zero remains ambiguous and the chance of burden shifting along the life cycle remains strong. Considerations like investments into research and development, synergistic emissions abatement of multiple technologies, dependence on background emissions etc. dictate the economic and environmental feasibility of technological choices in the value-chain. The current literature in the area focuses mainly on mature technologies. We build on this by including low technology readiness level (TRL) technologies within the life-cycle network superstructure to design temporally resolved net-zero, sustainable, circular value chains for chemicals and plastics.

A network model for the global chemicals and plastics production forms the basis of our framework. We model chemical processes at the value chain scale across life-cycle stages i.e., the transformation of fossil resources to platform chemicals, intermediates, fertilizers and polymers. The resulting life-cycle network may be parsed to yield a mapping of material flow across the supply chain. We supplement this network with data for emerging technologies such as the renewable power, carbon dioxide capture, electrified heating, the use of biomass-based feedstock, the electrochemical conversion of captured carbon dioxide to platform chemicals, recycling of plastics, and landfilling alternatives such as pyrolysis and incineration. We also allow functional substitutability between products. These models together constitute a superstructure network containing alternatives at all steps of the value chain. The underlying data are represented using the life-cycle assessment framework while the recently developed sustainable circular economy framework is used to handle circular flows. We develop a costing framework to estimate operating costs associated with emerging technologies, based on displacement at current product costs. We constrain the linear scale-up of bottom-up processes to meet the growing global demand of chemicals at discrete time steps. We model the evolution of TRLs according to experience curves. Stochastic effects as well as those of investment decisions on TRL evolution are incorporated. Additional constraints are levied to ensure the adoption of a technology only when it is sufficiently mature. The problem is formulated as a multi-objective optimization at discrete time steps where the set of allowed technologies, the final demand of products, the capital for investment, and the availability of natural resources and renewable electricity evolve with time and the system must reach net-zero emissions by a specific year, while minimizing capital, operational and investment costs.

Our results show that a combination of energy decarbonization and material recycling must be leveraged to reach net-zero. Material circularity allows for greater value addition while net-negative technologies such as biomass-based production offset emissions. Low TRL technologies allow greater value addition at lower emissions, subject to funds for their research and development and the availability of renewable power. Our roadmapping framework incorporates stochastic and economic considerations in decision-making processes, allowing the insights thus gained to guide the transition to net-zero.

Enabling sustainable chemical manufacturing from product to industrial ecosystem

Monday, 3rd July - 12:21: IE and Industry (short presentations) (B0.31 KOG)

Yizheng Lyu [1], ***Jinping Tian*** [1], ***Lyujun Chen*** [1]

***1.** School of environment, Tsinghua University*

The chemical industry is important to global economic development but arouses severe environmental effects and safety risks. Many chemical manufacturers keep aggregating in chemical industrial parks (CIPs), which largely promote material efficiency, environment, and safety performance by systematic and sustainable measures. To deliberately and rationally examine such evolution may help identify trackable development paradigms from forerunners and inspire followers to accelerate and maintain sustainability. This study defines a 3-stage evolutionary model of chemical manufacturing from separate production to an industrial ecosystem by analogizing the evolution of ecosystems and applies it to a typical chemical industry-intensive area where a 100-billion-CNY scale CIP locates. Corresponding to the model, the development of the chemical industry in the area can be divided into 3 stages: the emergence and development of chemical manufacturers (1979-1997), the establishment and expansion of the CIP (1998-2012), and the transformation to the industrial ecosystem (2013-now). The model is proven robust due to the same evolutionary tendency and attributes in practice as the model depicts. Five innovations undertaken in the practical evolution are summarized as references to promote the eco-transformation of CIPs, including (1) material and energy flow control, (2) green networking of supply chains, (3) reaction-engineering coupling industrialization, (4) reduction and resourcization of dilute acid and by-product salt, and (5) inherent safety improvement of whole-process chemical manufacturing. Further, the study analyzes that the driving force from Stage I to Stage II is simple economic benefits, but from Stage II to Stage III is a mixture of environmental requirements, safety production requirements, and economic benefits. The generalization and viability of the model are verified by the practice in HSEDA and other cases, and thus a new theoretical perspective can be proposed to summarize the general processes of process manufacturing development besides chemical manufacturing. It furthers the study of sustainable chemical manufacturing and profoundly influences eco-transformation practices.

Assessing material and energy networks in symbiotic petrochemical clusters

Monday, 3rd July - 12:28: IE and Industry (short presentations) (B0.31 KOG)

Michael Tan [1], ***Paola Ibarra Gonzalez*** [1], ***Igor Nikolic*** [1], ***Andrea Ramirez*** [1]

1. *Delft University of Technology*

To reach the sustainability goals of the European Commission, the petrochemical industry will have to transform from using fossil-based carbon sources to alternative carbon sources such as biomass and CO_2. Processes in a petrochemical cluster are, however, highly interconnected. Before a complex system such as a petrochemical cluster can be transformed, it is necessary to understand the level of interdependence among chemical processes, as changing or removing processes could result in potential cascading impacts, which are currently poorly understood. Therefore, there is a need to better understand the most important processes in a petrochemical cluster and their interactions. This study assesses a symbiotic petrochemical cluster's complex network properties and performance, identifying the essential processes and potential impacts.

In this work, complex network analysis used an in-house model of a representative cluster based on the petrochemical cluster of the Port of Rotterdam (PoR). The model used a bottom-up approach where 35 chemical processes and 18 utility generation processes were modeled using the process modeling software Aspen Plus. The models mimic the main characteristics of the processes in the PoR and generate detailed material and energy balances. To perform the network analysis, a Python module was developed to extract the balances from each Aspen Plus model. The data was used to construct a multiplex network of the representative cluster in Python using Py3plex. The network uses multilayered graph theory to represent the material and energy connections between processes as links, while the chemical and utility processes are represented as nodes. Each layer of the graph represents a different type of interconnection between nodes, and the only type of interlayer connections are with the counterpart of each node located in the other layers. The importance of the processes in the representative cluster was assessed by determining complex network properties such as degree centrality and strength. Additionally, key performance indicators (KPIs) such as CO_2 emissions and energy consumption were estimated to assess the performance at the system level of the petrochemical cluster.

The multiplex graph representation resulted in a network of 53 nodes with 62 material links, 54 steam links, and 22 electricity links on their respective layers. The strength of the nodes on the material layer based on the carbon mass flows pointed out that the olefins and ethylbenzene processes were the most important processes. While on the steam layer, the node strength showed that the aromatics plant and the refinery gas CHP were essential processes, and natural gas CHPs and Chlorine plants are the most important on the electricity layer. However, when considering the degree centrality of the material layer, the SMR unit providing hydrogen to other processes and the Ethylene Dichloride/Vinyl Chloride monomer process appear as the most interconnected processes. Not surprisingly, on the steam and electricity layers, natural gas CHPs are the most interconnected nodes of the cluster. The KPIs show that most CO_2 emissions come from utility generation units. However, the olefins plant has the highest direct CO_2 emissions as it burns byproducts to provide the heat required for the process. Additionally, they show that the olefins and aromatics plants are the most carbon-intense processes, as they respectively transform 37.0% and 45.8% of the carbon imported into the cluster into chemical building blocks and waste.

Global production division increases the iron ore supply chain fragmentation and risk

Monday, 3rd July - 12:35: IE and Industry (short presentations) (B0.31 KOG)

Ludi Liu [1]***, Xin Tian*** [1]

1. *Beijing Normal University*

The impact of global production division on resource supply chain security is increasingly notable in the context of recurring international conflicts. To address this pressing issue, we investigated the supply chain fragmentation (SCF) and resource risk of iron ores from a global value chain (GVC) perspective. Our results reveal a growing complexity in the GVCs of iron-embodied products, with over 60% of iron ores used in products processed by at least two countries. Intermediate goods trade has dominated the international trade of iron ore products, with embodied iron ore volumes 21 times higher than that in final goods. Notably, half of the top 20 iron-embodied product manufacturing countries exhibit conspicuous resource risk, with supply chain fragmentations (SCFs) exceeding 40%. Our findings emphasize the importance of enhanced trade policies and risk-mitigating measures tailored to the distinctive characteristic of local resources and industries to safeguard local resources and industries.

Keywords: Iron ore, Global value chain, Supply chain fragmentation, Resource risk, Multi-region Input-Output

New IE developments (short presentations)

Recent developments in Hybrid Life Cycle Assessment - A systematic review

Monday, 3rd July - 12:00: New IE developments (short presentations) (B0.13 KOG)

Rosalie Hagenaars *[1], **Ranran Wang** [1], **Reinout Heijungs** [2], **Arnold Tukker** [3]*

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Environmentally extended input-output analysis (EEIOA) and process-based life cycle assessment (LCA) are two of the most widely used methods for assessing the environmental impact of products and activities. However, both methods have limitations due to data availability and analytical scope. Therefore, researchers have investigated hybrid life cycle assessment (HLCA) methods to integrate the strengths of the two while mitigating the constraints. Previously, review studies have classified and explained the different HLCA approaches.

In light of growing policy analysis needs for environmental accounting, crucial methodological development has emerged in recent years, including initiatives of automizing hybrid LCA, the development of hybrid datasets, new methods for correcting double-counting methods, estimating missing inputs, and uncertainty analyses. Given these developments, it is crucial to review and understand the current state-of-the-art methodological developments and applications of HLCA, as well as reflect on the challenges and prospects that lie ahead.

To gain a comprehensive understanding of the current state-of-the-art in HLCA, we conducted a systematic review of 114 peer-reviewed HLCA studies published from 2015 to 2022. The presentation will delve into critical methodological developments, trends in applications, and environmental impact focuses. Additionally, it will address remaining data and analytical challenges, and outline future research needs, particularly in supporting upcoming climate policies and regulations.

SUSTAINABILITY ASSESSMENT OF EMERGING TECHNOLOGIES: TAILORING TO CONTEXT

Monday, 3rd July - 12:07: New IE developments (short presentations) (B0.13 KOG)

Gulnara Shavalieva [1], ***Henrikke Baumann*** [1]

1. *Environmental Systems Analysis, Chalmers University of Technology, 412 96 Gothenburg, Sweden*

There is a growing demand for the inclusion of environmental assessment early in the development process of emerging technologies. At the same time, the integration of the assessment is not an easy task due to the high level of uncertainty associated with the emerging solutions (Hetherington et al., 2014).

The predominant thinking about the use of the life cycle assessment (LCA) method is that the assessment is decision support, typically as a rational choice between two or more alternatives. This can be characterized as a "once and for all" approach. Several have pointed out problems with this approach: to produce results of the sustainability assessment, relevant to decision-makers, analysts need to place greater emphasis on the evaluation of the decision-making situation and procedure, i.e., the context of the LCA work (Baumann, 1995; Vermeulen, 2006). Pryshlakivsky & Searcy (2021) argue that LCA studies lack the evaluation from the viewpoint of those making decisions, as well as an understanding of the context under which decisions are made. Thus, to deliver useful LCA results, recognition of knowledge needs in the context and a context-tailored assessment are needed.

Given the lengthiness of technology development, involving multiple stages and a variety of actors involved, we believe that a more gradual assessment procedure with frequent dialogue with the decision-makers (i.e., users of the assessment results) might be beneficial. Depending on the technology development phase, the knowledge needs of the developers (decision-makers) might differ. From this follows that the purpose of the assessment, choice of a method, data requirements, and ways of communicating the results might vary at different stages of the technology development (different technology readiness levels). The context defines the questions the assessment answers, making them more meaningful and influential in the hands of the decision-makers. The role of the LCA analyst is to find a balance between adjusting to the knowledge needs of the decision-makers while advocating for environmental values.

The current work aims to identify the means for context-tailoring the sustainability assessment in technology development. By drawing on theories on systems thinking, decision and sense making, we want to better explore how context affects method choices in LCA modelling and governs the LCA procedure. There is a need for an alternative to the existing decision-making "singular actor, rational choice" approach – a more theory-informed alternative framework drawing from knowledge about LCA practice and decision processes could make LCA studies more effective in tech development.

A gradual approach where we not only try to understand the technical system to be modelled but also pay attention to the knowledge needs of the developers will be applied in an R&D project. In this project, we will not only conduct LCAs but also document the changing knowledge needs of the R&D project from lab bench to pilot plant. This will form the basis for a framework for tailoring LCA in tech development. The DECREASE R&D project, a multidisciplinary collaboration between Chemical engineering, Fluid dynamics, and Environmental System research groups, intends to investigate the carbonation of industrial alkaline effluents and residues at ambient conditions as a greener technique to capture and store carbon.

Prospective life cycle assessment: the way forward

Monday, 3rd July - 12:14: New IE developments (short presentations) (B0.13 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Rosalie van Zelm [1], ***Mark Huijbregts*** [1], ***Thomas Hennequin*** [2], ***Anne Ottenbros*** [3], ***Emma Zuiderveen*** [2], ***Mitchell van der Hulst*** [1]

1. *Department of Environmental Science, Faculty of Science, Radboud University, Nijmegen 6525AJ,* ***2.*** *Radboud University,* ***3.*** *Department of Environmental Science, Radboud University*

Prospective Life Cycle Assessment (pLCA) has been increasingly used to predict the future environmental impacts of emerging technologies. It allows an emerging technology, still in early development, to be modeled at a future, more-developed phase. Environmental hotspots in the production process can thus be found in an early phase of the industrial design planning. Furthermore, comparison of these emerging technologies to existing, mature technologies becomes more representative, which aids investors and policy makers in decision making. Several frameworks exist to perform pLCA. When applying pLCA to a specific case study a choice can be made for one framework, or a combination of multiple, depending on the case. However, while the frameworks are of help to systematically assess any case, they lack detail on application of specific estimation methods per case study.

The goal of our work is to develop a systematic and case-specific approach for upscaling environmental impacts, which can lead to realistic environmental impact predictions on industrial scale, so we can provide recommendations in an early-development phase.

To further refine existing approaches, we performed a variety of case studies, i.e. for photovoltaics, carbon capture and storage, direct air capture, a chemical synthesis, and chemical recycling of plastic waste. Our starting point was always the 5 steps for upscaling in the framework by van der Hulst et al. (2020), often supplemented with a specific framework focusing on the type of process or technology at hand. Whereas process changes, size scaling, and process synergies are needed to go from lab to industrial scale, industrial learning and external developments are applied from early to mature industrial production. Every step was addressed with a modeling or estimation method that varied depending on the case.

The main results and conclusions we found are that:

- expert consultation is key. While an LCA practitioner can perform the LCA on its own, there is no single method to go from lab to industrial scale that works for every case. The inventory and interpretation will be much stronger with expert input as upscaling is very case-specific. Ideally, this involves process simulations from technology experts.
- the end-of-life phase should not be disregarded. This is currently often done, since time lag between production and end-of-life can be substantial, making the latter very uncertain. However, instead of exclusion, scenario analyses should be performed to include circular options.
- allocation of multifunctional systems should be done based on the avoided-burden approach. This method provides some flexibility over system expansion as the fate of side-products is not always known. Moreover, it should be considered that avoided-burdens could change over time as replaced processes in the future could differ from processes that are replaced now, i.e. the counterfactual might change.
- Publicly available data for research is invaluable. This includes both historical environmental accounting for learning rate calculation, but also accessible prospective databases and background scenarios. These data should ideally be centralized and curated.

In the presentation, our results based on the case studies will be shown and the way forward presented.
Reference:

van der Hulst MK, Huijbregts MAJ, van Loon N, Theelen M, Kootstra L, Bergesen JD, & Hauck M. (2020). A systematic approach to assess the environmental impact of emerging technologies: A case study for the GHG footprint of CIGS solar photovoltaic laminate. Journal of Industrial Ecology, 24(6), 1234-1249. doi:https://doi.org/10.1111/jiec.13027

Reconciling the economic pillar of sustainability: A conceptual and methodological exploration on life cycle costing

Monday, 3rd July - 12:21: New IE developments (short presentations) (B0.13 KOG)

Chunbo Zhang [1]

1. *University College London*

“Life cycle sustainability assessment (LCSA) provides a framework for the holistic assessment of environmental, social, and economic impacts of products, in which life cycle costing (LCC) is incorporated as the “economic pillar” for economic sustainability assessment. In contrast to traditional costing approaches, LCC applies life cycle thinking to enable a comprehensive economic sustainability assessment. However, a plethora of disciplinary interpretations and adaptations of LCC can lead to terminological and methodological disparities and confusions. Here, through a literature review, this paper aims to reconcile the role of LCC in the LCSA framework to support decision making in economic sustainability assessment. We first investigated how LCC originated and has evolved from purely financial purpose to environmental and social aspects. We then introduced the emergence and development of LCSA and how LCC has been formulated in the overarching framework of LCSA. In addition, we discussed the challenges and opportunities to move beyond LCC to economic sustainability assessment, and found the potential pathway could be (i) employing a hybrid perspective to unify the actors along a production value chain, and (ii) adapting an economic impact assessment for an LCC. Finally, we discussed the five plausible aspects to define the system boundary of an LCC. Although this paper does not give straight answers to the existing debates on LCC and LCSA, it provides insights into reconciling the conceptual and methodological confusions in the application and development of LCC and LCSA.”

Disassembly analysis to promote rare earth permanent magnet recovery from end-of-life electric vehicle motors

Monday, 3rd July - 12:28: New IE developments (short presentations) (B0.13 KOG)

Thomas Maani [1]***, Sidi Deng*** [1]***, Lin Li*** [1]***, John Sutherland*** [1]

1. Purdue University

The growing number of electric vehicles (EV) will eventually lead to a comparable number of EV reaching their end-of-life (EoL). As a result, efforts are being undertaken to develop technologies and processes for circularizing EoL EV components such as traction motors through approaches like reusing, remanufacturing, and recycling. The disassembly of EoL EV motors is an unavoidable step in many such operations, and it is a difficult task due to unknown sizes and volumes, as well as considerable differences in motor design across different car types. The high expenses associated with the disassembly process have recently made it a prominent issue for research, particularly in the remanufacturing industry. In this study, we propose incorporating disassembly techniques into value recovery plans for traction motors in order to reduce landfilling and promote rare earth permanent magnet (REPM) reuse/recycling. This paper will explore a disassembly planning technique where an ideal disassembly sequence for the recovery of REPMs will be derived from priority matrices and disassembly graphs.

Towards automated mapping of global mining land use

Monday, 3rd July - 12:35: New IE developments (short presentations) (B0.13 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tim Werner [1]***, Victor Maus*** [2]***, Laura Sonter*** [3]

1. *The University of Melbourne,* ***2.*** *Wirtschaftuniversität Wien,* ***3.*** *The University of Queensland*

Advances in the quality and accessibility of satellite imagery have prompted rapid growth in research mapping the land footprint of mining. Multiple research teams have recently compiled open datasets with more than 150,000 polygons covering mining activities worldwide. These data help to explain the size, spread and nature of land use challenges linked to global material supply chains. Yet so far, it has only been viable to gather such data through a time-consuming manual process that requires trained analysts to visually recognise and delineate mine areas. Consequently, published updates on global mining land use are limited to approximately every two years. Meanwhile, mines are highly dynamic, constantly changing and expanding into new land. To keep pace with the real-time changes in mine areas globally, efforts to automate the task are needed.

This presentation outlines recent advances in the use of machine learning algorithms to automatically detect mine areas in satellite imagery. Building from this, we will discuss barriers and progress towards automating the global mapping of mine areas. Through a series of mapping case studies, we will also illustrate what levels of geometric and categorical accuracy can be achieved for different types of mine features, and for different parts of the world. Finally, we will discuss the implications of access to timely global mine land use data on broader field of industrial ecology, on governments, and the mining industry itself.

Food Systems (short presentations)

The Efficiency of dietary sustainability and its global transition

Monday, 3rd July - 12:00: Food Systems (short presentations) (B0.41 KOG)

Pan He [1]***, Zhu Liu*** [2]***, Klaus Hubacek*** [3]***, Giovanni Baiocchi*** [4]***, Dabo Guan*** [5]

1. *School of Earth and Environmental Sciences, Cardiff University, Cardiff, UK,* ***2.*** *Tsinghua University,* ***3.*** *University of Groningen,* ***4.*** *University of Maryland, College Park,* ***5.*** *University College London*

Global diets consume tremendous natural resources while causing multiple environmental and health issues. As the world faces challenges of adequate nutrition security with concomitant climate and environmental crises requiring urgent action, policies need to improve the efficiency of devoting environmental input of the food systems for health benefits. Here we evaluate the global transition of such efficiency in the past two decades represented by health benefits obtained per unit of 4 key environmental inputs (GHG emissions, stress-weighted water withdrawal, acidifying emissions, and eutrophying emissions) in 195 countries. We find that the efficiency of each environmental input follows an N-shaped curve along the Socio-Demographic Index (SDI) gradient representing different development levels. The efficiency first increases by benefiting from the eliminated stunting with a larger abundance of food supply, then decreases driven by climbing environmental impacts from a shift to animal products, and finally starts to slowly grow again as countries shift toward a healthier diet. Our efficiency indicator offers an improved understanding of nutritional transitions in terms of environmental impacts and a useful way to monitor the transition of dietary patterns, set up policy targets, and evaluate the effectiveness of specific interventions.

Opportunities for mitigating greenhouse gas emissions in U.S. beef production

Monday, 3rd July - 12:07: Food Systems (short presentations) (B0.41 KOG)

Rylie Pelton [1], *Clare Kazanski* [2], *Shamitha Keerthi* [2], *Kelly Racette* [2], *Nathaniel Springer* [1], *Michael Wironen* [2], *Eugene Yacobsen* [2], *Sasha Gennet* [2], *Deepak Ray* [1], *Kris Johnson* [2], *Jennifer Schmitt* [1]

1. University of Minnesota, Institute on the Environment, 2. The Nature Conservancy

Each year, the U.S. processes ~33 million head of cattle to produce over 27 billion pounds of beef, making it the largest producer of beef in the world (USDA 2022). U.S. beef supply chain actors are increasingly committed to reducing GHG emissions in response to the growing urgency and direct, material impacts of the climate crises (Thompson 2022). However, while decision makers across the beef supply chain – particularly producers, feedlot operators, processors, and retailers – aim to reduce the GHG impacts of beef production, identifying where and which intervention strategies to prioritize remains a significant challenge and barrier to progress (Thompson 2022). The U.S. beef supply chain is one of the most complex food production systems in the world (Suszkiw 2019), but it lacks transparency, which prevents processors, food companies and other key downstream decision makers from identifying where and how to most effectively target efforts to reduce and mitigate GHG emissions. Because the movement of cattle and feed through the various stages of production is currently not traceable in the U.S., models are needed to estimate subnational commodity flows and corresponding impacts unique to different regions (Karakoc et al 2022, Smith et al 2017). Existing life cycle assessment (LCA) models aggregate impacts by commodity categories and do not connect these subnational flows to spatially explicit environmental impacts, and, consequently, do not estimate reduction potential of regionally specific production practices nor the unique supply chain connections that result in spatially variable impacts in downstream stages of the supply chain (Rotz et al 2019; Castonguay et al 2023, Asem-Hiablie et al 2019). Characterizing such differences in solutions across production stages and regions is critical to prioritizing and deploying interventions.

Our study provides the first spatially-explicit, fine-scale “cradle-to-gate” assessment of GHG impacts and mitigation opportunities of the U.S. beef supply chain. We identify emission hotspots and quantify individual and combined reduction potentials from applying different interventions across locations and stages of the supply chain, quantifying the baseline greenhouse gas (GHG) emissions and mitigation opportunities of 42 practices spanning the value chain from crop and livestock production to processing. This is accomplished by linking the spatially determined impacts of production across the entire beef supply chain with a transport cost-minimization model that connects subnational agricultural commodity flows (feed and cattle) and individual beef processing facility demand.

We find that up to 71% of the baseline GHG emissions could be reduced through full implementation of a set of alternative practices across feed production (10%), grazing (56%), confinement (4%) and processing (1%) phases, equivalent to 142 MMT CO_2e reduced each year relative to baseline. Emissions reduction and mitigation opportunities in the feed production, grazing and feedlot phases vary spatially across the country, yet large-scale adoption of opportunities across all phases of the beef supply chain are important. This new approach bridges a critical gap in information necessary for decision makers to prioritize the deployment of emissions mitigation strategies in the U.S. beef production system, providing a roadmap for industry stakeholders to identify promising locations and practices to invest in to advance mitigation goals, and helping propel the industry to meet climate action targets in the U.S.

Fingerprint 2 Footprint: Enhancing environmental sustainability of animal feed production by combining NIR spectroscopy and environmental footprinting

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:14: Food Systems (short presentations) (B0.41 KOG)

***Maria Cairoli* [1], *Anne Ottenbros* [2], *Sin Yong Teng* [1], *Mark Schoot* [3], *Steef Hanssen* [4], *Christiaan Kapper* [3], *Rosalie van Zelm* [4], *Mark Huijbregts* [4], *Jeroen Jansen* [1]**

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Motivation and aim: The necessity of incorporating environmental criteria in decision making is increasingly recognised by stakeholders. However, environmental considerations are not always in synergy with economic profit. A better understanding of potential synergies between reducing both economic and environmental costs may therefore lead to more sustainable production strategies and win-win situations. The aim of this study is to explore the relationship between economic and environmental costs of animal feed production recipes and whether synergies are possible. We do this by combining NIR spectroscopy, chemometrics and in a complementary tool to optimize recipe formulations while enhancing the economic profit, lowering the environmental footprint and maintaining quality standards.

Approach: Animal feed recipes contain a combination of different raw materials (i.e. crops), grown at various origins and processed at different locations. NIR spectroscopy allows for non-destructive, cost- and time-efficient, and accurate characterization of the nutrient composition of crops. The accuracy of NIR spectroscopy allowed prediction of the origin country of crops based on the nutrient composition. Country specific environmental footprints, expressed in terrestrial ecosystem quality loss (EQL) and climate change (CC), were calculated by combining life cycle assessment (LCA) data of agricultural practices, regional yield and regional lost carbon sequestration capacity of natural vegetation (i.e. foregone sequestration). Regional data was used and subsequently grouped country specific footprint distributions. This information was combined with time-varying crops' prices in a stochastic multi-objective optimization to obtain a set of optimal formulations (i.e. pareto front) with minimum price and environmental impact. The optimization model included nutrient constraints to guarantee feed quality.

Preliminary results and relevance: The obtained pareto front from the optimization model results in recipes for feed formulations with both lower economic and environmental costs compared to benchmark recipes. Using variability in prices and environmental impact per country and crop type, and accurate nutrient compositions of crops from NIR spectra as a basis for feed formulations, our approach provides a realistic and robust view of possible variation. This results in country and crop specific recommendations for recipe formulations, which in turn can help companies to make decisions to achieve environmental and quality targets without additional costs. These results show that our unique approach of combining accurate NIR spectra with chemometrics and LCA works and recipes with high synergy between economic and environmental costs are obtained.

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Food delivery packaging in China: Environmental impact reduction potential from circular economy approaches

Monday, 3rd July - 12:21: Food Systems (short presentations) (B0.41 KOG)

***PEIXIU CHEN* [1], Benjamin Steuer [1]**

1. The Hong Kong University of Science and Technology

The emerging online-to-offline (O2O) food delivery service has become increasingly popular in China. However, the growing food delivery services industry has led to the excessive use of single-use packaging and cutlery, which is a particularly problematic part of the global waste and climate change challenge. What complicates matters is the absence of circular economy strategies, such as reducing, reusing, and recycling (3R) to eliminate packaging waste and pollution in the city. The sustainable transition of food delivery services has a significant contribution to achieving zero-waste and low-carbon development.

This study aims to explore the packaging waste dilemma from the food delivery services industry and quantify the potential environmental benefit of circular economy solutions by life cycle assessment. These findings are used to identify and determine the best practices of circular economy schemes in the food delivery service industry.

A bottom-up approach was conducted to identify the type and amount of packaging and cutlery waste generated by meal and drinks food delivery service through a sample survey. The food delivery services in typical a 20km^2 district within a commercial and residential area in Guangzhou, China was selected as a case study. A cradle-to-grave life cycle assessment was used to evaluate the environmental impact of food delivery services packaging and cutlery production and its end-of-life treatments. The environmental impact of circular economy solutions of (a) increasing the collection and recycling rate of packaging waste, (b) reusable food packaging deposit system, and (c) reducing cutlery consumption were also compared with the current system. Finally, the feasibility of the implementation of circular economy strategies to food delivery services in the context of China's recent plastic reduction policy.

The results indicate that over 100 tons/ yr of packaging and cutlery waste was generated and plastics waste accounted for more than 80%. Increasing the collection and recycling rate of packaging waste by 35% of packaging can reduce greenhouse gas (GHG) emissions from drinks and meals orders, by 70% and 74%, respectively. Moreover, when implementing a reusable food packaging system by use of deposits, the GHG emission would correspond to a decrease in the current impact on the climate change by one-third. In addition, the GHG emission of reusable food packaging deposit systems can be further reduced to 17% and 23% when no cutlery providing. GHG emissions, respectively. This study provides empirical results on food delivery service waste generation by transparent bottom-up method and highlights the environmental benefit of circular economy strategies adoption of this industry, which offers support to the policymakers in the field of food delivery service waste management.

Keywords: Life cycle assessment; Food delivery services; Packaging and cutlery waste; Circular economy; China

The transition of sustainable food consumption: scenario analysis and psychological factors

Monday, 3rd July - 12:28: Food Systems (short presentations) (B0.41 KOG)

Yinglei WU [1], Kiyo Kurisu [1], Kensuke Fukushi [1]

1. The University of Tokyo

One-third of the anthropic greenhouse gas (GHG) emissions are associated with the food system in the world. The transition towards more sustainable food consumption will play a vital role in global GHG emissions mitigation. Several diet choices are perceived to reduce environmental burdens at the life cycle stages of the food system. Organic food, seasonal food, local food, and plant-based diet are the most popular issues concerning the environmental impact resulting from agricultural production, which contributed to 72% of food-related GHG emissions. Besides, unpackaged food, sustainable cooking, food waste reduction, and household compost are also hot issues regarding the stages of packaging, consumption, and waste treatment.

Majorities of relevant studies have used life cycle analysis (LCA) to estimate the environmental burdens of different diet choices. Among these studies, several researchers conducted scenario analysis to predict the future trend. However, a comprehensive study incorporating all the major sustainable diet choices is still lacking. Furthermore, previous scenario-analysis studies were mainly based on assumptions, without considering the actual consumer acceptance of different diet choices. In this study, we will combine the LCA and questionnaire surveys to estimate the environmental burdens of key consumer choices, and conduct the scenario analysis based on people's acceptance of the diet transition from the questionnaire surveys. Consumer motivations and barriers regarding sustainable diet choices will also be identified.

Before the surveys, we conducted a cluster analysis of the food consumption structures worldwide to decide the target areas. The results showed that global food consumption can be divided into nine clusters. The consumptions of beef and milk in Cluster 9 (major Asian countries) were less than 30% of Cluster 1 (major European countries and Russia) and Cluster 2 (major American countries and Australia). Considering the high GHG intensity of beef and milk, the Asian diet would be more environmentally sustainable. Thus, we picked China among Asian countries, owing to its large population and rapid socioeconomic transition in recent years. We further conducted the cluster analysis on the Chinese diet structures at provincial levels, and six clusters were identified. Accordingly, one sample province was selected within each cluster, and Beijing and Shanghai were also included to understand the trends in most developed provinces in China.

The questionnaires include measurements of environmental awareness, eating habits, cooking, and shopping behavior routines, frequencies of protein intakes, motivations and barriers of key sustainable diet choices, preference, and acceptance towards protein alternatives, personalities, and perception of eating. Online surveys were conducted in Beijing and Shanghai in December 2022. The results showed that over 50% of people refused to "stop eating meats" or "just eating vegetables". However, 80% of people were acceptable to replace beef with chicken, and 76% accepted the replacement of beef with pork. The major barriers were the worries of malnutrition and taste. The correspondence analysis results showed that the motivations and barriers to choosing organic food were different from other diet choices; "healthy", "environmentally friendly", and "safe" were the major motivations to choose organic food, while "expensive" was the major barrier. The online surveys based on the same concept will be also conducted in the selected six provinces.

Metrics for absolute environmentally sustainable foods – case on tunicate burger

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:35: Food Systems (short presentations) (B0.41 KOG)

Lars Gunnar Furelid Tellnes [1], ***Anna-Lena Kjøniksen*** [1]

1. Østfold University College

As food has a substantial contribution to several environmental areas, the food industry is developing new products with lower impacts. These products need labels and metrics so that the lower environmental impacts can be communicate with consumers. To make the right investments for such new products, it is important to know both current and potential future environmental metrics. For food products, it is highly important to reduce environmental impacts such as climate change, eutrophication, and biodiversity. These areas are all major importance according to the planetary boundaries concept. Within life cycle assessment (LCA) methods that are typically applied on products, there has been an increased focus on absolute environmental sustainability. For climate change and food, this has for instance been estimated to a limit of 0.5 kg CO2 per meal. The objective of the study is to assess methods based on LCA to evaluate the absolute environmental sustainability of new food products with a case study.

The case study focusses on products based on tunicate (Ciona Intestinalis), which is a marine invertebrate potential as feed ingredient and human consumption. It is newly registered as a feed material in the EU and salmon feed are among targeted applications. It also has potential for human consumption and a burger patty is being developed for the conscious consumer. Tunicates can be farmed similar to mussels, where they eat plant plankton. Nutritionally, tunicates are high in protein and omega-3 making it similar to fish meal. Environmentally it is interesting for its low land use, low carbon footprint and no feed production needed. The tunicate consumption of plant plankton is assessed to have a benefit to environment by nitrogen removal from marine waters.

The goal of the LCA within the study is to assess the potential impact of the tunicate burger patty and to compare with metrics for absolute environmental sustainability. LCA is applied and based on the framework for environmental footprint (EF). Special focus has been given to LCIA and eutrophication, as the impacts on nitrogen flows is of interests. To assess the absolute environmental performance, various criteria from literature is reviewed.

The results indicate that the climate performance of the tunicate burger is within the criteria for absolute sustainability. A large share of the impacts on climate change is linked to the diesel used in harvesting, while capital goods such as equipment and machinery also has a large share. For eutrophication, the results become negative in total as the effect of nitrogen removal are surpassing the other impacts. As there are no negative thresholds, weighting was applied to assess the total sustainability. With EF methods, the weighted results in total with all impact categories. The results indicate that the tunicate burger is well suited for absolute environmentally sustainable foods. Further work is however needed in making absolute criteria for covering all environmental impact categories.

Energy (short presentations)

Energy and feedstock: Material Flow Analysis of Fossil-based Chemical Production in China

Monday, 3rd July - 12:00: Energy (short presentations) (B0.16 KOG)

Yuheng Cao [1]***, Meng Jiang*** [2]***, Bing Zhu*** [1]

1. Tsinghua University, 2. Norwegian Univ. of Science and Technology

Burning coal, crude oil, and natural gas promotes development while threatening climate goals. Fossil fuels are generally used both as energy to drive processes, and feedstock to synthesize materials. While the energy use dominates fossil fuels consumption, the feedstock use of fossil fuels, mostly in the chemical industry to produce plastics, fertilizers, and chemicals, is tightly bound with production processes, could hardly be substituted, and associated with huge carbon emissions. The chemical sector is therefore known as "hard-to-abate" sector. The governance of fossil fuels requires not only a focus on the energy system but also an understanding of their feedstock use in the chemical industry, which is expected to have a large expansion potential in the coming decades. However, our knowledge about fossil-feedstock-related process and hard-to-abate chemical production is limited.

China is the largest fossil fuel consumer and has the most comprehensive, large-scale chemical sector in the world. It is responsible for nearly half of the global chemical sector's energy consumption and carbon emissions. Investigating China's chemical sector could also provide insights for the global chemical production. Based on our knowledge, we have yet to see a study portraying the big picture of how the chemical industry utilizes fossil fuels as feedstock along with the downstream chemical production in China.

Here, we open the black box of fossil fuels consumption and downstream chemical production in China. We developed an unprecedentedly detailed, localized chemical process and reaction database and model for the macro-level mass balance of China's chemical industry. We mapped detailed mass and carbon flow through the complex interwoven network constituting China's chemical industry. We further linked the feedstock source and carbon emission to the processes. We used uncertainty analysis to determine the potential deviation of results.

Among our findings, we reveal 4.6(±1)% of coal consumption, 14.9(±0.2)% of crude oil consumption, and 7.1(±1)% of natural gas consumption were used as feedstock in China's chemical industry. Only 64(±2)% of carbon elements in fossil feedstocks are accumulated in products while the remaining were emitted. Over 75% of methanol, ammonia, and PVC plastic production relied on the feedstock of coal and was responsible for 2-3% the total emissions in China. China faces a dilemma of balancing carbon-intensive coal-to-chemical production with a high reliance on imported crude oil and natural gas supplies. We also analyzed different low-carbon technologies and approaches for decarbonization of the hard-to-abate sector.

This interdisciplinary work is delivered by chemical engineers, industrial ecologists, environmental scientists, economists, and industry practitioners together. We think it makes an excellent, multidisciplinary contribution to the current knowledge of fossil fuels, chemical production, circular economy, and climate change mitigation. It could also provide a foundation to couple with integrated assessment models (IAM) and shared socio-economic pathways (SSPs) to understand the dynamics and levers for societal transformation towards a net-zero emission circular economy specifically the role of the chemical industry as well as the details of material cycles.

Urban Indian Residential Buildings: Now and in the future

Monday, 3rd July - 12:07: Energy (short presentations) (B0.16 KOG)

Aishwarya Iyer [1]***, Mohamed Aly Etman*** [2]***, Edgar Hertwich*** [3]***, Narasimha Rao*** [4]

1. *Center for Industrial Ecology, Yale School of the Environment, Yale University,* ***2.*** *Yale School of Architecture, Yale University,* ***3.*** *Norwegian Univ. of Science and Technology,* ***4.*** *Yale School of the Environment, Yale University*

Soon to be the most populated country in the world, India expects a rapid increase in residential floorspace, with projections saying 20 million square meters will be constructed between 2015 and 2030. While this is a threat to global climate change mitigation efforts to remain within planetary boundaries due to India's emissions intensive power sector, this can also be an opportunity to transition to better practices. This is helped by the fact that India does not suffer from technological lock-ins like high-income countries do. Therefore, it is crucial to study the urban residential sector in India, and to identify opportunities to manage this growth efficiently. Life-cycle analysis (LCA) is an important tool used to quantify impacts from the residential sector, but previous LCAs from India have only focused on formal buildings, while 25% of urban Indian people live in informal settlements. We previously defined a three-building type framework to capture the diversity of buildings across low-and-middle-income countries including India, and in this study we use this framework to identify energy and material efficient strategies for the urban Indian residential sector.

Cooling is expected to be the fastest growing end-use this decade, as 1.8 to 4.1 billion people in the Global South are disproportionately affected by global warming, and lack access to indoor thermal comfort. We find that heat stress is especially acute for residents of informal settlements, due to untenable housing and lack of access to cooling appliances. Another characteristic buildings in India is the dense clustering in local neighborhoods, which has been found to reduce cooling demand by over 40% in case studies from other countries. We factor in the differences in envelope materials, surrounding buildings and locations for the three building types, formal, semi-formal and informal, and quantify the thermal comfort gap. We then introduce innovative interventions ranging from new envelope materials to new types of appliances, to cater to a population unable to afford air-conditioning.

We consider both temperature and humidity, two key variables in thermal comfort perception, and use a composite metric named the heat index to quantify thermal comfort gaps. Across three metropolitan cities covering three major climate zones, we find different degrees of temperature and humidity-based discomfort. This helped us recommend cooling appliances like dehumidifiers and humidifiers to complement the existing ventilation and fan-based cooling strategies. Combined with different envelope materials, these help reduce the total life-cycle energy demand while meeting thermal comfort benchmarks. We also find that the cluster of surrounding buildings can improve the perceived thermal comfort by up to 40%, and varying the cluster parameters, especially for informal settlements, can be one way to reduce the thermal comfort gap.

In summary, this study is inclusive in considering residential buildings housing different economic classes of residents in India, and introduces several novel modeling elements that better capture the local conditions. We compare material and energy efficiency strategies across three building types, and identify technical and behavioral pathways which also help meet thermal comfort requirements in an increasingly hot part of the world.

Using different transport modes: an opportunity to reduce UK passenger transport emissions?

Monday, 3rd July - 12:14: Energy (short presentations) (B0.16 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hugh Thomas [1]

1. University of Cambridge

The transport sector accounted for 34% of territorial UK greenhouse gas emissions in 2019. Furthermore, there has been limited progress in decarbonising the UK transport sector, with sector emissions falling by only 1.6% between 1990 and 2017. Alongside technological shifts and improvements, shifting from the least to the most energy efficient modes of transport is widely recognised as an effective strategy to reduce transport emissions and energy use. This modal shift can lead to rapid and sustained emissions reductions, whilst simultaneously leading to improvements in air quality, reduced urban congestion and population health benefits. To date, many studies and targets only consider modal shifts from one mode to another making it difficult to understand the overall potential impacts of modal shift towards low emitting transport modes.

This study aims to quantify the realistic potential for reducing emissions through modal shift in the UK passenger transport sector. A discrete choice model is used with data from the UK National Travel Survey to determine the least emissions intensive mode of transport that could feasibly be used for each trip. Travel time expenditure, transport mode accessibility, transport network capacities, trip characteristics, and passenger attributes are all considered restrictions that constrain which modes of transport can be used. A sensitivity analysis is performed to identify which factors have the biggest impact on the feasible extent of modal shift. Thus, the actions that should be prioritised to encourage a shift away from emissions intensive transport modes are determined. Total domestic passenger transport emissions can be reduced by 31% without reducing overall mobility or relying on technology development and deployment. This emissions saving is achieved through a 38% reduction in the annual average passenger-km travelled by car and 630% and 210% increases in the annual average passenger-km travelled by cycling and rail respectively. Transport policy should focus on increasing cycling by investing in cycling infrastructure to improve safety and increasing rail use by reducing passenger costs and improving service quality.

Linny-R: Elegant diagram-based modeling and simulation of (smart) clusters, energy grids and markets

Monday, 3rd July - 12:21: Energy (short presentations) (B0.16 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Pieter Bots [1]

1. *Delft University of Technology*

Climate change, recent geopolitical tensions and the need for a more circular economy force industry, energy systems operators, and market regulators to adapt. This poses strategic decision making challenges that call for simulation models to assess the consequences of large scale variable renewable energy sources (vRES), storage, interconnection, demand response and power-to-X, and to appraise strategies for capacity expansion and other investments at multiple spatial and temporal scales. Enterprises need to evaluate business cases for these investments while negotiating with potential partners as they explore opportunities for industrial symbiosis. Grid operators have to deal with large uncertainties in capacity demand, which makes robust network expansion planning more challenging.

There appears to be no lack of specialized software tools, but rather of policy modeling capabilities. Tools for policy modeling should (1) permit modeling and analysis of synergies across sectors and temporal scales in high resolution, (2) provide open access and transparency, and (3) further engagement and trust between model developers, policy/decision-makers and other stakeholders (Chang et al., 2021; Ryszawska et al., 2021).

The executable graph-based notation Linny-R (https://linny-r.info) fits the need for easy-to-build, easy-to-understand, easy-to-use and easy-to-share models. It permits modeling and simulation of complex unit commitment systems without having to write software code. The graphical notation for networks of processes, products and flows in a cluster hierarchy is concise, yet expressive enough to represent technical aspects (storage, losses, minimum part load, ramp rates, spinning reserve) as well as economic aspects (fuel, start-up and shutdown costs, capacity expansion, investment options, cost of capital).

To facilitate experiments under numerous scenarios, model parameters and outcome variables can be specified as (conditional) arithmetical expressions. A rolling time horizon and automatic scaling of time series data facilitate simulation of unit commitment over thousands of time steps on any discrete time scale. Ex-post cost price calculation affords inferring market prices and producer surplus.

The Linny-R modeling tool provides an intuitive WYSIWYG model editor for networks, datasets, charts, and experimental designs. Easy navigation through the cluster hierarchy, and seamless transition from editing a model to executing it, facilitate interactive participatory model development. The software is platform-independent, and runs in all modern internet browsers. It is open source, available under the MIT license (https://github.com/pwgbots/linny-r), and can be linked to any MILP solver.

Linny-R has been used by undergraduate students with only basic Operational Research training to simulate industrial ecosystems and (transboundary) energy markets, assess the flexibility and vulnerabilities of industrial clusters, and identify robust investments in network components, storage and power-to-X. Examples of these models (Antwerp industrial cluster, network expansion planning, effects of interconnection on regional e-prices and producer surplus) and their output will be presented to demonstrate that the graphical notation is indeed easy-to-learn for people with limited training in OR.

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Market and Grid Required for Renewables-Dominated Electricity Systems

Monday, 3rd July - 12:28: Energy (short presentations) (B0.16 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Gjalt Huppes [1], ***Ruben Huele*** [1]

1. *Leiden University, CML*

Renewables and Batteries

Wind and solar electricity are both non-dispatchable and intermittent. They will expand dramatically in primary production of electricity. Final use of electricity is also intermittent, and not aligned with intermittent supply. Reserve capacity can equalize electricity production and use, as with pumped hydro, flywheels, condensers, and: batteries. Decentral batteries will develop a combined capacity able to overcome the difference between primary production and final use over days to weeks, see (Xu, Behrens et al. 2023). Discarded car batteries add to this *secondary production capacity* in the longer term, with later recycling. Batteries can react to price changes in milliseconds, helping stabilize the grid automatically. But will this all happen in the current electricity market and the current grid, in Europe tending towards renationalization? Certainly not!

Market and Grid

Markets have developed for wholesale high-voltage production, at time scales of days, hours, and shorter. Wholesale producers are thus linked to high-volage Transmission System Operators (TSOs) responsible for voltage and frequency stability. For demand variation, also at lower voltage levels, some market mechanisms have developed, least so in the low-voltage decentral domain. Using car batteries for secondary production will only come if the selling price is higher than the buying price for charging the battery. Car batteries function for the car anyway, so they come nearly for free.

In the grid-to-come, with distributed production at all voltage levels, bidirectional flows must be accommodated. Long-distance transport lines are needed from areas with cheap solar and wind to high-use areas.

Design principles

-The grid system consists of independent nodes, with multiple line connections between them.
-The grid system is near continental.
-Producers are connected to at least one node, preferably more.
-Nodes can contain transformers, to link between different voltage lines.
-Internal grid lines and inter-grid lines can create flexibility, also for supporting grid stability.
-New millisecond electronics allow for real-time grid stabilization.
-Prices are variable at milliseconds level, for all market participants.
-Electricity from a node must have an equal price for all purchasers, at any moment of time.
-Grid transport costs in each node must be covered as part of the price of electricity sold.
-Congesting damage in a grid node must be prevented at any time.
-Congestion pricing, steeply rising, is the prime means to prevent congestion damage.
-Proceeds of congestion pricing go into a public fund for grid improvement.
-Private monopolies in the grid system must be prevented, as are public monopolies where possible.
-Each node operator can acquire electricity from several linked nodes and from external producers.
-Each node operator sells electricity to other grid nodes, and to users.
-There are no fixed connection costs, similar to other markets that do not charge for the right to shop.
-Price and quantity information for all flows is real-time available for grid node operators and clients.
-He who owns a market shall not trade in that market.

Results

Variable priced primary and secondary markets can solve the intermittency problem of renewables automatically.
Avoiding monopoly in node markets induces lowest production cost. Any final user receives electricity for the lowest possible cost, also dynamically.
The collectivity of Transmission System Operators is responsible for grid design and development at all voltage levels.
Car batteries can earn back many thousands of Euros over their lifetime.

EEIOA cases 1

The exotic species footprint of traded commodities

Monday, 3rd July - 15:00: EEIOA cases 1 (B0.13 KOG)

Jan Borgelt [1], ***Francesca Verones*** [1], ***Konstantin Stadler*** [1]

1. NTNU

Globally, numbers of exotic species in different ecosystems are on the rise. Apart from conscious releases and escapes from enclosures, accidental introductions via transported goods are the main reason for this. At the same time, the quantity of traded commodities between countries is increasing. Once exotic species become introduced into new environments, they can establish, become invasive and consequentially threaten the ecological balance of invaded ecosystems. Ecosystem impact footprints of anthropogenic resource uses have been quantified previously by combining Multiregional Input-Output analyses (MRIO) and Life Cycle Impact Assessment (LCIA) for different impacts, i.e., climate change, terrestrial acidification, marine and freshwater eutrophication, land stress and water stress. Unlike traditional footprinting approaches, ecosystem impact footprints go beyond the reporting of resource use and emissions and consider their consequential environmental effects. However, to date, the ecological impacts of exotic species introductions were not considered within this framework. Here, we contribute towards a more complete analysis of global consequences of resource use by accounting for the impacts caused by the trade-mediated transport of exotic species. We utilize a recently developed LCIA methodology that expresses the environmental consequences of traded goods in a potentially disappeared fraction (PDF) of native species per kg of transported commodity between 36,975 different combinations of importing and exporting countries. We coupled this to EXIOBASE and the BACI trade database to retrieve invasive species footprints of bilateral trade flows at product level across various commodity groups, including manufactured goods, raw materials as well as agricultural products. We analyzed potential impacts embodied in traded goods due to aiding introductions of exotic species. The findings highlight countries that considerably drive the relocation of exotic species and their consequential impacts.

Tracing carbon footprints to supply chain intermediaries in the United Kingdom

Monday, 3rd July - 15:15: EEIOA cases 1 (B0.13 KOG)

Diana Ivanova [1], ***Hanspeter Wieland*** [2]

1. University of Leeds, 2. University of Natural Resources and Life Sciences (BOKU)

Several decades of informed warnings about climate change have been insufficient to reverse trends of rising greenhouse gas (GHG) emissions and ecological degradation. While environmental impact assessments usually do not engage with the concept of power directly, power dynamics permeate the adopted approaches and recommended strategies for impact reductions. The complexity of global supply chains – which is high and rising - has also impaired discussions about responsibility, power and agency.

In the context of environmental impacts, agency and power are highly connected as higher agency in terms of impacts corresponds to power in terms of contribution to the problem and ability to influence systemic change. Debating agency and power over impacts have direct implications for the plausible mitigation strategies as well as targeting injustice. Historically, environmental impact assessments have focused on the origin and consumption ends of supply chains, overlooking the role of powerful intermediary actors.

Here, we provide a complementary approach to traditional production and consumption perspectives by presenting a detailed analysis of intermediary industrial contributions and tracing emissions across production layers. We perform the analysis for the carbon footprint of the United Kingdom's gross production (GP) with the updated EXIOBASE multiregional input-output (MRIO) version 3.8.1 for 2019, which describes the global economy in the detail of 200 products, 44 countries and 5 rest-of-the-world (RoW) regions. The UK's GP carbon footprint captures all commodities produced within the UK for intermediate and final consumption, regardless whether they are consumed inside or outside the UK. As both the MRIO model and code are openly available via Zenodo and Github, our analysis can be easily replicated for other countries, years, environmental and social stressors (e.g. energy use, water, land, employment).

We find that 54% of the GHG emissions associated with UK gross production in 2019 originate within four major source industries, including fossil fuel-based extraction, manufacturing and electricity, animal-based food, and air transport. Furthermore, the distribution of emissions and value added provides implications about mitigation capacity and spatial justice.

Quantifying and understanding urban metabolism based on the national socioeconomic metabolism

Monday, 3rd July - 15:30: EEIOA cases 1 (B0.13 KOG)

Sónia Cunha [1], Paulo Ferrão [1]

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Cities are critical components of the complex system that is the socioeconomic metabolism of a country. While they may have high resource productivity associated to a focus on services, they are dependent on material flows from other regions, and therefore an understanding of these interdependencies are fundamental for the transition to a sustainable development paradigm as it provides inputs to promote resource productivity at a broader level.

The quantification of urban metabolism can be challenging and time-consuming, resulting in various data sets that may have diverse and non-comparable structures. In this work, we characterized the urban metabolism of the Lisbon Metropolitan Area (Lisbon henceforth) using a methodology based on data that is typically available from official sources, creating a set of data that can be compared to the national socioeconomic metabolism of Portugal and replicated for other regions and countries. The national metabolism was quantified in physical input-output tables (PIOTs) using a recently published methodology based on material flow data and monetary input-output tables (MIOTs). The urban metabolism material flows were calculated using a top-down approach, where various sector-specific parameters were used to downscale the national material flows to the urban level. The scaling parameters included the number of workers per sector, the energy consumption per sector, the number of animal heads, land use, and population.

In 2017, Lisbon had 27% of the total national population, covered 3% of the territory, accounted for 36% of the national gross domestic product (GDP), and had a GDP/cap that was 30% higher than the national average. The comparison between the Portuguese and urban metabolism of Lisbon showed differences not only in the economic structure but also in the materials used and resource productivity of the economic sectors. Lisbon has a lower share of fossil fuels and metallic minerals, while the share of non-metallic minerals is higher. The material structure of the economic sectors also presents differences, particularly in the manufacturing sector, which uses a larger share of biomass and a smaller share of non-metallic minerals, in Lisbon. While Lisbon accounts for a small share of the national material output from the manufacturing sector (14%), it accounts for a significant share of the resource use of services (36%). Not only does Lisbon have a higher contribution of services to its value-added (87% versus 75%), but the resource productivity of services in Lisbon is also higher (3.49 €/kg versus 3.01 €/kg). The results suggest that both the economic structure and the differences in the sectors themselves contribute to Lisbon having a higher overall resource productivity than Portugal. The representation of both the urban and the national metabolism in the form of chord diagrams clearly illustrates the differences between the Lisbon material flows and the national flows and their interdependencies.

This work showed how a top-down model could be used to characterize the metabolism of an urban area, which is a critical contributor to the national GDP, and how it differs from the national socioeconomic metabolism. Understanding urban metabolism and the relation between the urban area and the other regions of the country can have a meaningful contribution to the development of national and regional sustainable development policies, as is the case of circular economy plans that can benefit from information such as the flows in the critical value chains of the economy.

Evaluating the decoupling of economic growth from material consumption based on the socioeconomic metabolism characterization of European countries

Monday, 3rd July - 15:45: EEIOA cases 1 (B0.13 KOG)

Sónia Cunha [1]***, Marta Abrantes*** [2]***, Patrícia Baptista*** [2]***, Paulo Ferrão*** [3]

1. *Institute of Environmental Sciences (CML), Leiden University, Leiden, the Netherlands,* ***2.*** *IN+ Center for Innovation, Technology and Policy Research, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Portugal,* ***3.*** *IN+ Center for Innovation, Technology and Policy Research, LARSyS, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal*

Increasing levels of natural resource use are resulting in negative impacts on the environment, and the monitoring and evaluation of their pathways at national levels, with discrimination of the socioeconomic metabolism is critical for sustainable development. Cunha and Ferrão (2021) provided a significant contribution, by developing a general methodological framework to quantify the dynamics of resource productivity of economic sectors based on the compilation of monetary and physical flows making use of publicly available data. Considering the need to pursue a more sustainable use of resources, the relationship between economic growth and resource consumption is explored in this paper for a wide group of European countries.

This work aims to identify drivers or characteristics of the socioeconomic metabolism of each economy which might explain different decoupling indexes based on either the domestic material input (DMI) or raw material equivalents (RME). Firstly, countries are classified by a decoupling index based on DMI per capita and gross domestic product (GDP) per capita or RME per capita and GDP per capita. The countries are then grouped according to how the economic development has been decoupling from both DMI and RME, only DMI, or neither. Secondly, the socioeconomic metabolism of the nations in each group is analyzed for drivers that can explain the observed development trends.

The analysis of the socioeconomic metabolism covers a variety of indicators, including those related to the development of the country (DMI, RME, GDP, and population density), the consumption of specific materials (domestic extraction and imports by materials), economic structure (value-added and resource use by economic sector), resource productivity by sector, and material and monetary exchanges between economic sectors, that can be used to identify key value-chains in the economy. This analysis is enabled by calculating physical input-output tables (PIOTs) per country.

The use of raw material equivalent consumption is essential since it enables the quantification of the resource use of countries, extending the previous methodology. By considering raw materials equivalent consumption, we can account for the extraction of raw materials associated with imports, and consider those impacts across borders in our analysis. For example, in countries with little industry whose demand is mostly associated with the needs of the population and services, the impacts associated with imports may be large enough to change the conclusions on whether the economy has even decoupled economic growth from resource use.

As a result, the application of an innovative framework is established in this work and applied to a variety of European countries, providing an important step to a better understanding of the implications of economic growth in resource consumption, for countries characterized by different socioeconomic metabolisms.

References:

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Special Session: Plastics, Chemicals and Sustainability (Part 2)

How to feed the global population with less greenhouse gas emissions from nitrogen fertilisers?

Monday, 3rd July - 15:00: Special Session: Plastics, Chemicals and Sustainability (Part 2) (A0.51 KOG)

***Yunhu Gao* [1], *André Serrenho* [1]**

***1.** University of Cambridge*

Food security relies on nitrogen fertilisers, but its production and use account for approximately 5% of global greenhouse gas (GHG) emissions. Meeting climate change targets requires the identification and prioritisation of interventions across the whole lifecycle of fertilisers. Although existing literature provides compelling examples of how to mitigate GHG emissions from the production and use of synthesised nitrogen fertilisers, so far a global assessment of GHG emissions from nitrogen fertilisers has not been established. Such assessment can enable the prioritization of the mitigation potential of various interventions often only assessed in isolation in the literature.

We have mapped the global flows of fertilisers and their emissions for 2019, along all stages of the lifecycle, by reconciling the production and consumption of nitrogen fertilisers and regional emission factors in nine world regions. We have then used this material flow analysis to explore the maximum mitigation potential of various interventions to reduce emissions by 2050.

We found that approximately two thirds of fertiliser emissions take place after their deployment in croplands, and only one third takes place at the production stage. Feeding the growing global population with less GHG emissions from nitrogen fertilisers would require a decarbonisation of the production of fertilisers by electrification of heating and the deployment of water electrolysis for ammonia production. However, this would have to be combined with interventions at the use-phase, such as an increase in nitrogen use efficiency in croplands to its maximum potential, a deployment of nitrification inhibitors, and a shift in the mix of fertilisers used globally. These are all options with high technology readiness levels, and our results shown that if these interventions are deployed, up to 84% of global GHG emissions of synthetic nitrogen fertilisers can be reduced by 2050. We also found that, unless there are meaningful changes in the manure management process that can substantially reduce emissions, the use of manure in croplands as an alternative to synthetic fertilisers results in more GHG emissions.

Driving a Net-Zero U.S. Ammonia Industry Considering Technology Evolutions and Policy Strategies

Monday, 3rd July - 15:15: Special Session: Plastics, Chemicals and Sustainability (Part 2) (A0.51 KOG)

Banafsheh Jabarivelisdeh [1], ***Enze Jin*** [1], ***Phillip Christopher*** [1], ***Eric Masanet*** [1]

1. *University of California, Santa Barbara*

Ammonia production is a highly energy and emission intensive process accounting for around 1.8 % of global CO_2 emissions and it is poised to increase substantially to provide nutritional well-being to a growing global population. While fertilizer demand reductions are one important solution, shifting remaining demand to low-carbon production systems will also be required to achieve net-zero ammonia cycles by mid-century. To reach a net-zero future of U.S. chemical sector, the ammonia industry must find a way to decarbonize its production. In this study, a bottom-up model with high technical and economic resolution is implemented to identify least-cost potential pathways to achieve a net-zero ammonia industry in U.S. by 2050. Different low-carbon technology options including water electrolysis, carbon capture, utilization and sequestration (CCUS), methane pyrolysis, and bio-based gasification for ammonia have been considered by compiling a technology dataset including technical and economic data. The results indicate that water electrolysis plays a key role in the net-zero pathway for U.S. ammonia industry by supplying around 50% of ammonia demand in 2050, while the remaining ammonia is mainly produced by CCUS-equipped natural gas autothermal reforming process. In the perspective of system costs, reaching a net-zero ammonia industry by 2050 requires 55% additional costs compared to business-as-usual scenario (with no mitigation actions). Sensitivity analyses are then conducted to assess the sensitivity and dependency of the net-zero transition pathway to the variations in key performance and economic parameters of emerging low-carbon technologies (in particular for water electrolysis and methane pyrolysis), and to identify the tipping points required for improving their economic competitiveness overtime. Furthermore, Besides, the role of policy interventions through carbon pricing (for different system emission boundaries) and tax credits implementation for incentivizing near-term deployment of low-carbon technologies are addressed. Considering upstream emissions (during natural gas acquisition) along with the direct and indirect emissions of ammonia production routes, this study reveals that a carbon price of $400/t$CO_2$ can induce the adoption of low-carbon technologies including water electrolysis to achieve the net-zero pathway by 2050.

A dynamic material flow analysis of the global demand of polymers

Monday, 3rd July - 15:25: Special Session: Plastics, Chemicals and Sustainability (Part 2) (A0.51 KOG)

Yunhu Gao [1], ***André Serrenho*** [1]

1. *University of Cambridge*

Introduction

Polymers are ubiquitous thanks to their low-cost and versatile properties. The production of plastics has increased from 1.7 Mt in 1950 to 368 Mt in 2019[1]. The wide application of polymers has led to a series of environmental issues, including greenhouse gas (GHG) emissions and ocean pollutions. The life cycle of polymers accounts for 4.5% of the global GHG emissions[2].

In order to reduce the environmental impact of polymers, capping the production and consumption of polymers is proposed by researchers[1,3–5]. Circular economy is also proposed to reduce the waste of polymers[6,7] and reduce production. However, a global model to quantify the practical limitation of circular economy and demand reduction is not available yet.

Material flow analysis is widely adopted to investigate the global and regional mass flow of polymers[8]. However, a holistic breakdown of polymer's mass flow in each world region is missing. Few studies forecasted the future demand of polymers by extrapolating the historical consumption[8–10], but the accuracy of regional demand of polymers is disabled or compromised by the lack of regional granular data to fit the model, e.g., production and trade of polymer raw materials and products with embedded polymers.

Method

To bridge the gap, the study adopts the dynamic material flow analysis model to quantify the production, trade, and consumptions of 11 groups of polymers (LDPE, LLDPE, HDPE, PP, PS, PVC, PET, PU, rubber, fibres, and other plastics) and 1205 products made of polymers in nine world regions from 1978 to 2020, and fits the historical trend in order to forecast the future regional and global demand of polymers in different scenarios.

Results and discussion

Among the 8.86 Gt cumulative consumption of polymers, 2.41 Gt polymers are still in-use in 2020. Among all the regions, Northeast Asia ranks the first, covering 28% of the total stock in-use, and North America, Europe and South Asia are responsible for 20%, 19% and 10% of the total stock in-use, respectively.

In terms of application sectors, 51% of the in-use stocks takes place in building and construction, due to the long average residence time of 35 years. 19% plastics is used in the transportation sector. The other sectors are responsible for less than 10% of the total in-use stocks.

The stocks in-use per capita in Oceania and North America are 1.28 t/cap and 1.27 t/cap, respectively. The average stock in-use in Europe is 840 kg/cap, and all other regions have less than 400 kg/cap. As the regional GDP per capita increases, the regional stock in-use per capita also increases, which is the basis for the forecast of future demand of polymers in different scenarios.

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Re-evaluation of end-of-life treatment options for plastics

Monday, 3rd July - 15:35: Special Session: Plastics, Chemicals and Sustainability (Part 2) (A0.51 KOG)

Fanran Meng [1], ***Jonathan Cullen*** [1], ***André Serrenho*** [1]

1. *University of Cambridge*

The desirability of plastic products has led to unprecedented growth in demand since the 1950s when the first successes in mass production were achieved. Since 1990, growth in plastic production has surpassed steel, glass, and aluminium such that in 2017 the global plastic output stood at 438 Mt. This growth in plastic use has profound consequences for our climate and our planet. By 2050, assuming no deceleration in plastic consumption, our cumulative plastic waste output will have exceeded 26,000 Mt. Of this, almost half will have been discarded to landfill or the environment.

Clearly, this prompts questions about the end-of-life (EOL) options for plastics. Understanding the merits and demerits of different EOL options will be essential to determine if a change in strategy is required. Developed countries have long prioritised recycling but are now reliant on developing countries to handle their growing surplus of polymer waste. Meanwhile, municipal landfill sites and energy recovery facilities continue to emit megatonnes of greenhouse gases along with a panoply of toxic chemicals.

Comparison between EOL options is difficult to standardise. Recycling intersects with manufacturing; landfill and incineration are the building blocks of municipal waste infrastructure; and energy recovery from the combustion of polymers currently serves the electricity and heating demand of cities. The problem not only overlaps multiple industrial sectors but multiple academic disciplines too. The uptake of recycled polymer is market-mediated, so the economic realities have to be explored to determine if the engineering ideals can ever be realised.

This study re-evaluates recycling, landfill, and incineration for commodity polymers (PET, PE, PVC, PP, PS, PUR, and ABS). This involves the compilation of a repository of life cycle inventory data, a review of the academic and grey literature, and some original modelling, which are synthesised to create a decision-making framework. Policy options for reducing the greenhouse gas emissions of the different EOL options are discussed.

We find that we should not be incinerating fossil-derived plastic waste, as we do currently. We should continue to recycle as far as this is reasonably practicable and we should create more favourable conditions for industry and consumers to recycle their waste. If waste cannot be recycled, and for those waste types for which recycling will never be possible, landfilling is the least-worst option, so long as the polymer is durable and residual emissions can be captured.

Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 2)

Towards a framework for inclusive and circular urban waste management systems: regeneration as a binding element

Monday, 3rd July - 15:00: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 2) (C1.31 KOG)

Daan Schraven [1], ***Liang Dong*** [2]

1. *Integral Design & Management, Delft University of Technology,* ***2.*** *City University of Hong Kong*

The rapid urbanization in combination with unsustainable production and consumption patterns leads to the generation of substantial amounts of urban waste. The circular economy is a concept which promises to bring solutions both with top-down activities (related to the implementation of policies which are based on the waste hierarchy principles by the local governments) and with bottom-up activities (such as the adoption of circular business models by private and public sector stakeholders). However, a circular economy does not automatically endow cities with inclusiveness or resilience against shocks. Consequently, any decision which relates to the transition to a circular economy is not trivial for social inclusion and system resilience. This chapter explores and discusses how to account for circularity and inclusion aspects simultaneously in urban planning and development with a particular focus on urban waste management systems. To this end, we present an integrative framework to assist urban decision makers in considering inclusion and circularity where urban regeneration can play the role of a binding element. The framework places explicit attention towards improving the accessibility of social groups to various forms of capital and stimulate the development of local economies through improved circulation of resources within the urban fabric.

A study on maximizing energy efficiency of manufacturing and disposal of plastics for the promotion of carbon-neutral plastic circular economy

Monday, 3rd July - 15:08: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 2) (C1.31 KOG)

Minoru Fujii [1], *Satoshi Ohnishi* [1], *Seiya Maki* [1], *Kosuke Kawai* [1], *Liang Dong* [2]

1. National Institute for Environmental Studies, 2. City University of Hong Kong

The sustainable use of plastics requires that their manufacturing and disposal processes, including recycling, be carbon neutral. However, except for pre-consumer plastics and post-consumer plastics that can be easily sorted and collected as single materials, it is difficult to recycle them at a high yield and with the same quality as virgin products. In addition, as plastic containers and packaging are being replaced by biodegradable materials and paper, it is expected that it will be difficult to economically maintain the conventional high-quality plastic recycling system. Chemical recycling, which is considered to have a wide range of acceptable waste, still has an insufficient carbon yield, and biomass plastics cannot be said to be carbon-neutral, depending on the status of the biomass used as a raw material.

Considering such backgrounds, to make a path of carbon recycling even for the waste plastic that is generated mixed with other materials and garbage, and as a result, its incineration is unavoidable due to the difficulty of sorting, a system which supplies electricity and heat for plastic manufacturing through incineration of combustible waste while simultaneously captures CO2 from the gas after incineration and synthesizes low-molecular-weight organic compounds as raw materials for plastic manufacturing will be a complementary and essential technology in the future.

The production process of plastics consumes a large amount of electricity and heat, and it is very efficient, especially if the heat is supplied from a waste incineration plant. The synthesis reaction from CO2 to chemical raw materials consumes more hydrogen than the stoichiometric ratio of hydrocarbons, resulting in an exothermic reaction of about 300°C, but this heat can also be effectively used in the plastic manufacturing process. In the future, renewable electricity will become the first primary energy available to mankind, and the only resource that is allowed to be burned will be waste that is difficult to be recycled (biomass will be given priority to its use as materials). In such a situation in the future, the high-temperature heat required in the plastic manufacturing process will be supplied from waste and renewable electricity, and to ensure a stable supply of heat from fluctuating electricity, one option is to supply heat after converting electricity to hydrogen. If so, the input of hydrogen to the synthesis reaction is not wasted because it is effectively used for heat supply after all. Based on the above consideration, a carbon recycling system, which resynthesizes plastic from unrecyclable waste through CO2 by incineration, can be comparable to other recycling methods in terms of energy efficiency and economic advantage, if the heat utilization efficiency of the system is maximized. We will report our investigation on such a system.

Impact Assessment on Direct Circulation of Positive Electrode Active Materials from Spent Lithium-ion Batteries Through Innovative Separation Technologies

Monday, 3rd July - 15:16: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 2) (C1.31 KOG)

Yi Dou [1]***, Aya Heiho*** [1]***, Izuru Suwa*** [1]***, Yasunori Kikuchi*** [1]

1. *The University of Tokyo*

With the rapid popularization of electric vehicles, formation of a closed loop circulation for spent vehicle Lithium-ion batteries (LIBs) has become a critical issue in the field of circular economy. Although recycling technologies such as hydrometallurgical treatment and pyrometallurgical treatment after crushing and grinding process have been indicated feasible to recover critical metals from LIBs which has been practiced in worldwide demonstration projects, they cannot avoid massive input of chemicals and energy in processing. By contrast, innovative separation technologies, such as electrical separation method using single pulsed power to separate cathode particles from Al foil, enable direct reuse of recycled positive electrode active materials (PEAMs) for battery cell remanufacturing that can significantly reduce economic costs and environmental impacts. Thus, before commercialization a total assessment on the potential scale of treatment by innovative separation technologies and its impacts on the resource and environment is crucial to catch the opportunities and risks for making better technology development and diffusion strategy.

This study proposes a recycling system for spent LIBs where electrical separation method is adopted, while developing an integrated assessment approach to evaluate the potential overall impacts from innovative separation method on the circulation of critical metal resources for LIBs through combining a dynamic material flow analysis on critical metals and prospective life-cycle assessment on the resource consumption and environmental impacts during LIB production and recycling. Taking the rapidly increasing domestic electric vehicle (EV) market of Japan as a case, this study takes various key influencing factors into scenarios, such as model change of LIB in the future and secondary usage of LIB for stationary power storage, to quantify the impact variation affected by policies and external factors. In addition, conventional treatment methods including incineration/landfill, crushing with hydrometallurgical and pyrometallurgical treatment are also evaluated for comparison.

Results from the model indicate the obvious merits to introduce innovative separation technology for direct recycling PEAMs for battery cell remanufacture, but the resource and environmental impacts are quite affected by policies and external factors. In detailed, 1) all the recovered PEAMs can be directly used in battery cell remanufacture even considering the fast model change of vehicle LIBs, because the rapidly expanding EV market in Japan is large enough to accept them; 2) direct circulation of PEAMs will bring about much lower carbon emissions and resource consumption than conventional treatment methods, but these merits will be weakened by secondary usage of spent LIBs because the decarbonization of power system in near future can reduce the overall emission intensity in battery production and recycling; 3) despite introducing innovation separation technology into recycling system or not, the case of secondary usage of spent LIBs will increase around 10% net input of critical metals comparing to the case without secondary usage; 4) a dilemma will appear in resource management policy that the introduction of innovation separation technology prefers no secondary usage of spent LIBs, while the conventional treatment methods prefer doing secondary usage of spent LIBs. From the perspective of reducing long-term environmental impact and resource consumption, the suggestion from this study is to earlier introduce innovative separation technology and speed up the direct circulation of PEAMs without secondary usage of spent LIBs.

A solution in household: Is there an alternative beyond the currently widespread pathways of food waste management?

Monday, 3rd July - 15:24: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 2) (C1.31 KOG)

Hengxing Yin [1], Ling Han [1], Xin Tong [1]

1. Peking University

As China's urban population grows and the mandatory implementation of the waste classification policy in 2019, the increasing food waste gives a great burden on existing infrastructures like landfills, composting and incineration whose content, in the long run, would not be effective enough. The efforts from individuals and households may become the key to this solution. A key challenge for the sustainability of food waste management is the question of making a systematic assessment and how much the household can play their roles in the effectiveness of the food waste hierarchy in achieving more efficient resource use and reducing environmental impacts. To fill this gap, this paper develops an alternative path beyond the currently widespread methodologies focusing on separately collected and composted household organic waste (especially home composted). Using data collected from a field experiment in Beijing and other official sources, this paper presents here several scenarios evaluating this claim. Our scenarios have revealed three core insights. First, under the implementation of the waste classification policy, home composted reduces great pressure on infrastructures. Second, composted household organic waste works well with greenhouse gas emissions but needs adjustments for other social impacts. Third, there are numerous barriers to the prioritization of household composted food waste, such as management and infrastructure at the community level. This study proposes a scheme for China presenting a realistic and comprehensive alternative path with household participation in China's waste management.

Just transition: moving toward socio-ecological justice in the sustainable development era

Monday, 3rd July - 15:32: Special Session: Trans-continental research agenda for inclusive circular urban industrial innovation systems (Part 2) (C1.31 KOG)

Yuhang Sun [1], *Liang Dong* [1]

1. *City University of Hong Kong*

Just transition has received much attention recently, especially considering the integration of just transition with the sustainability transition. Up to now, research on just transition has paid more attention to social justice, while the ecological justice consideration is still inefficient. However, as we consider sustainable development in the framework of the socio-ecological system, justice to society and justice to ecology should not be considered separately. In this paper, we recall that the trending notion of socio-ecological justice should be an explicit pursuit during the just transition process. Inductive, deductive, and abductive analysis has been used to determine socio-ecological justice's origin and its increasing dimensions. We figure out that socio-ecological justice originates from the intersection of the development of the socioeconomic system, the development of nature concerning, and the development of concepts and theories of justice. By summarizing the grassroots social movements relevant to socio-ecological justice and the development of environmental justice concepts, together with the distribution, participation, recognition, and capabilities dimension from the environmental justice theory, we figure out that the inclusiveness dimension should be included in the framework of socio-ecological justice in this sustainability transition era. Inspired by the concepts of restorative justice and cosmopolitan justice, the inclusiveness dimension means a broadened scale and scope of socio-ecological justice consideration for humans, non-humans, and ecosystems all over the world. In conclusion, we suggest that more inclusive socio-ecological justice should be an explicit pursuit during the process of just transition in this sustainable development era.

MFA case studies 2

Coexistence of improving material flow indicators and reducing carbon emissions in Japan

Monday, 3rd July - 15:00: MFA case studies 2 (A1.44 KOG)

Sho Hata [1], ***Keisuke Nansai*** [1], ***Kenichi Nakajima*** [1]

1. *National Institute for Environmental Studies*

Material production is a significant contributor to carbon emissions, highlighting the importance of material management in achieving carbon neutrality. In Japan, improvements in four material flow indicators (MFIs) have helped facilitate the transition to a more sustainable material-cycle society. However, the specific economic and technological drivers that have led to changes in these MFIs are not clear, and it is uncertain whether further improvements of MFIs would contribute significantly to Japan's journey toward carbon neutrality. In this study, we developed the structural decomposition analysis that identifies the key change drivers in MFIs and carbon footprints (CF). The study period is from 2011 to 2015, during which all MFIs improved in Japan and national greenhouse gas emissions decreased. We identified drivers in the material supply chain that produced improvements in the MFIs, and among these drivers, those that simultaneously reduced CFs. Our findings indicate that changes in MFIs at the national level are not dependent on isolated factors, but rather on a combination of economic and technological drivers. Notably, supply chain structure is a common factor for the four MFIs, but it positively impacted resource productivity and final disposal, while negatively impacting cyclical use rates. Additionally, some of these changes have also led to an increase in carbon emissions. We find that the resource productivity and cyclical use rates in the supply chain of scope 3, including the production of goods and services and fixed capital formation, had inconsistencies ranging from 40% to 70%. Our results further reveal that while changes in the supply chain and fixed capital formation led to improvements in two MFIs (resource productivity and material circularity), these same changes also resulted in an increase in emissions. To address this conflict, producers need to recognize the nexus between material consumption and carbon emissions and manage both in an integrated manner, paying particular attention to their capital-embodied supply chain. An integrated assessment of material use and carbon emissions would help to chart a more effective path to carbon neutrality, avoiding inconsistencies between reforming material flows and reducing carbon emissions.

Dynamic material flow analysis of lithium-ion battery materials: The impact of vehicle sharing

Monday, 3rd July - 15:15: MFA case studies 2 (A1.44 KOG)

Daniel Johansson [1], *Simon Davidsson Kurland* [2], *Johannes Morfeldt* [1]

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The electrification of passenger cars has already taken off, while the expansion of shared and autonomous vehicles has yet to emerge. For succeeding with the electrification Lithium-ion battery (LIB) materials need to be used efficiently. A system based on shared (autonomous) cars will likely reduce the stock of cars as compared to a system based on private cars. However, shared cars will likely be used more intensively (in terms of annual distance) and the lifetime of the car will likely be shorter (doi.org/10.1038/s41467-022-33666-2). This will have an impact on the need for LIB materials.

In this study we analyze how a transition to electrified and shared mobility could impact the flows and stocks of Li, Ni and Co using Dynamic Material Flow Analysis (MFA) and a vehicle stock turnover model (doi.org/10.1016/j.trd.2021.102807). We analyze different assumptions on the transition to electrification and sharing, on how many private cars a shared car substitutes, on the impact driving intensity has on vehicle lifetime, and on battery chemistry. The model is calibrated to the car ownership and use pattern of Swedish metropolitan residents.

As indicators of material efficiency, we use gross and net inflow (i.e., gross inflow minus gross outflow) of material per annual person kilometer (pkm). In the two example scenarios presented in the abstract we assume that batteries are NMC 622, while also alternative assumptions will be included in the presentation. In Scenario 1 sharing is negligible and in Scenario 2 we assume a transition to shared vehicles. By 2050, 98% of potential car buyers choose a shared option, compared to 2% in 2023. The expansion of sharing is based on a Gompertz function. One shared car is assumed to substitute five privately held cars. Further, we assume that by 2035 all new vehicles are battery electric vehicles (BEVs). The annual distance travelled by car is the same in both scenarios.

In 2050 for Scenario 1 the gross inflow of Li, Ni and Co are 19, 80, and 27 mg per pkm. If recycling is implemented fully, around three quarters of the required amounts of raw materials could come from recycled batteries. For Scenario 2 the gross inflows of Li, Ni and Co per pkm are cut roughly in half, and the amounts of material that can be obtained from scrapped BEVs is higher than what is needed in the production of new BEVs. This a result of that the transition to BEVs is assumed to occur earlier than the expansion of sharing, implying that the scrappage of old private BEVs will be larger than the inflow of new shared BEVs.

In the sharing scenario the stock of the LIB materials is reduced by a factor of about three. The reason why the stock is not reduced by a factor of five, as one shared car substitute five private cars, is that some private cars are still used in 2050. Further, the gross inflow is only about halved, because of that the vehicle calendar lifetime drops with usage intensity, leading to an increased turnover rate in the system.

Sharing is likely to increase material efficiency, but the details depend on assumptions. In the presentation we will further explore the impact of these assumptions on the dynamics of the flows and stocks of the LIB materials.

ASEAN4 EW-MFA with Perspectives on Well-Being Indicators

Monday, 3rd July - 15:30: MFA case studies 2 (A1.44 KOG)

(Anthony) Shun Fung Chiu [1]***, Liang Dong*** [2]***, Marianne Faith Martinico-Perez*** [1]

1. De La Salle University, 2. City University of Hong Kong

Natural resource is the engine for economic development and resource efficiency is critical to realize the sustainable development goals (SDGs). This study performed as a first try to comprehensively investigate the resource flows and productivity transition under resources policies development, and their coupling to well-being indicators in 4 ASEAN countries, including Philippines, Indonesia, Malaysia and Thailand. Economic wide material flows analysis (EW-MFA) and resource efficiency & productivity index was applied to near 50-year MFA data (1970-2017), with localization. MFA indicators were further coupled analyzed with well-being indicator like HDI index (available from 1990s). National-wide resource policies in the four countries were reviewed to enlighten critical insights behind the MFA indicators. Results highlighted a fluctuated but gradual improvement of resource efficiency and productivity, together with a spiral up of well-being. However, the fluctuation also indicated a challenge on resilience of economy, which will in return affect the resource indicators.

How much sorting is required for a circular low carbon aluminium economy?

Monday, 3rd July - 15:45: MFA case studies 2 (A1.44 KOG)

Julien Pedneault [1], Guillaume Majeau-Bettez [1], Manuele Margni [1]
1. CIRAIG, Polytechnique Montréal

Circular economy aims to reduce primary material consumption, waste generation, and emissions while reducing environmental impacts (Korhonen et al., 2018). Many approaches exist to achieve this objective, but recycling is the most studied of them (Kirchherr et al., 2017). For the case of the aluminium industry, which has already a long history of recycling, efforts toward greater material circularity are motivated by important potential reductions in environmental impacts. However, aluminium recycling follows a downcycling dynamic where wrought alloys are transformed into cast alloys, accumulating tramp elements at every cycle. With the saturation of stocks of aluminium and the reduction of the demand for cast alloy due to electrification of transport, improvement in the recycling system must be made to avoid a surplus of unused recycled aluminium, reduce the overall environmental impacts of the industry, and move towards a circular economy.

Aluminium sorting is a key towards a low impact industry, but a full transition to a circular business model is challenging due to the high number of alloys available, the labor cost of properly sorting these materials, and the difficulty to identify specific alloys (Gaustad et al., 2012). Improving the system from a low sorting and downcycling dynamics towards a better sorting system would require additional efforts not only in terms of human and financial resources, but also in new logistic activities. Those extra activities would consume additional energy and material leading to a hypothetical trade off between extra sorting effort and overall environmental impacts.

No study has been done so far to evaluate the relationship between sorting intensity and primary material displacement. Here, we aim to evaluate the potential environmental benefits of improving sorting efforts by combining operations research, prospective material flow analysis and life cycle assessment. Our optimisation model defines how to minimise climate change impacts according to different sorting efforts, dismantling conditions, and collection rates.

While inter-alloys contamination limits the benefits of recycling, the results has shown that an optimal sorting could reduce the primary aluminium production by 30% in 2050. This leads to an annual reduction of greenhouse gas emissions of 30% in comparison to a no sorting scenario. The sorting needs become more and more important as the accumulation of aluminium stock in the Technosphere slows down and the end-of-life flows of aluminium to be recycled increase over time. Enhanced dismantling leads to bigger reduction of environmental impact (45% of reduction by 2050 in comparison to the no sorting scenario) by limiting contamination prior the recycling itself. An increase of collection rate could even lead to a decoupling between the demand of aluminium and the environmental impacts of the industry when combined with appropriate sorting and dismantling. We also identified different closed-loop recycling that should be promoted in priority in specific sectors, like the building and construction and the aluminium cans.

Results have shown how a circular transformation of the aluminium industry has clear co-benefits on its decarbonisation and other environmental indicators. To implement a better material circularity, the mobilization of different stakeholders is needed. From a wider perspective, this research shows how operations research can be used to project a circular future in a specific industry.

Advances in MFA methods 2

Taxes and crises: modeling time-dependent changes in lifetime

Monday, 3rd July - 15:00: Advances in MFA methods 2 (B0.17 KOG)

Kamila Krych [1], ***Johan Pettersen*** [2]

1. NTNU, 2. Norwegian Univ. of Science and Technology

Dynamic material flow analysis typically treats lifetime as a purely cohort-dependent concept. The lifetime is modeled as inherent to the product cohort and it stays unchanged throughout the product life, limiting it merely to technical characteristics determined by the producer. However, the reality is clear that product lifetime can also be affected by external factors such as consumer preferences, availability of certain services, and the condition of the economy together with people's disposable income. Recent examples show that even the global pandemic can temporarily influence material cycles, e.g., by extending the lifetimes of electronic products which cannot be replaced due to a shortage of electronic components, or by shortening the lifetimes of kitchen appliances and furniture which were discarded in great quantity due to a high renovation activity during the pandemic. To model such effects, lifetime needs to be dynamic and dependent on more than just the cohort; currently, there is no tool allowing for dynamic lifetime modeling in MFA.

This work introduces the Dynamic Lifetime Model (DLM), which is a Python-based method allowing users to define lifetime as a function of both cohort and time. The DLM is equipped with functions that facilitate the handling of a dynamic lifetime and performs dynamic stock and flow calculations using a lifetime defined in such a way. The calculations are done using a hazard function instead of a conventional survival function, which makes product outflows in a given year dependent exclusively on the preceding year's stock. The DLM class is fully compatible with the ODYM framework, used by many researchers in the MFA community.

The DLM enables incorporating time-dependent factors into MFA models, which can reflect short-term disruptions to material turnover rates. It also opens up modeling possibilities for slowing down material flows through product lifetime extension. Strategies for longer life modeled using DLM can include cohort-dependent ones such as design for durability, but also time-dependent ones such as, e.g., lowering the tax on spare parts, repair services, and second-hand goods. Such lifetime extension strategies take effect on various timescales, and they involve various stakeholders, which increases the policy relevance of scenarios created using DLM.

Regional Sensitivity Analysis to determine the appropriate combination of CE strategies

Monday, 3rd July - 15:15: Advances in MFA methods 2 (B0.17 KOG)

***Yusuke FUJII* [1], *Ken MATSUOKA* [1], *Ryu Koide* [2], *Shinsuke Murakami* [1]**

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Regional Sensitivity Analysis (RSA) is a graphical approach in sensitivity analysis, based on Monte Carlo simulations, to determine the parameters having significant impacts on the values in the simulation model. In this presentation, we demonstrate how RSA works with the future material flow forecasts by the population balance model (PBM).

There are high expectations for the implementation of various Circular Economy (CE) strategies, and it is necessary to use an appropriate combination of multiple strategies. While some studies have evaluated the implementation of individual CE strategies, none have evaluated the implementation of multiple strategies. Therefore, this study aims to develop a simulator, which can identify the critical parameters and support decision-making regarding the implementation of CE strategies for consumer durables. The novelty of the research is the ability to quantitatively assess the benefits to society, in various contexts, based on the stock and flow of products; the ability to evaluate multiple strategies, including combinations of strategies; and the incorporation of the sensitivity analysis method to take uncertainty into account in simulations based on Material Flow Analysis.

There are five CE strategies that can be considered in the model: reusing, remanufacturing, recycling, rental and extension of usage period. PBM is adopted to calculate the flow of the products using the Duration of Use (DoU) distribution. Model input comprises the implementation rate for each CE strategy and other parameters such as collection rate and rental period. The output is comprised of three evaluation indicators, the amount of the residuals to be landfilled, Total Material Requirement (TMR) and Greenhouse Gas (GHG) emissions. Regional Sensitivity Analysis is applied to identify critical parameters, including uncertainty.

Case studies were conducted on digital cameras and smartphones in Japan to confirm the functionality of the tool and to consider the implications for the target cases. It was found that parameters such as the collection rate to the formal route, the reuse rate via consumer-to-consumer and second-hand stores, and the percentage of DoU extension played particularly important roles in improving the evaluation indicators. In the case of digital cameras, which have a relatively low environmental impact during production, the risk of GHG emissions rebound effect due to rental was found to be significant. For smartphones, for which the demand is not expected to decrease, the impact of the ratio of DoU extension on the evaluation indicators was particularly strong.

We found out that RSA works particularly well with material flow forecasts. By updating the distribution of variables in the Monte Carlo simulations, it is possible to increase the accuracy of the whole prediction. It is expected that such information will be added in the future to enable more detailed analysis.

Parameter reconciliation for designing biophysically consistent socio-technical alternatives

Monday, 3rd July - 15:30: Advances in MFA methods 2 (B0.17 KOG)

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A research axis of the STEEP team (steep.inria.fr) wishes to enrich debates around possible alternatives by helping actors produce narratives of the future which are consistent from a biophysical viewpoint (see e.g., Giampietro, 2021). The approach adopted does not seek to optimize the existing system but to imagine and assess radically different futures. In an ever more constrained world, this means being able to identify and decide on trade-offs relative to the different aspects of the problem (Courtonne, 2016).

We define a socio-technical alternative as a consistent arrangement of modes of production and modes of consumption. This includes biophysical and socio-political dimensions, but for the time being the emphasis is laid on the circulation of materials, energy and human work between sectors and down to final consumption.

In the MFA field, data reconciliation enables to translate incomplete and inconsistent data to flows respecting e.g., mass conservation. This relies on constrained optimization; it was in particular popularized by the STAN software (Cencic, 2008) and proves very useful to describe the state of past or current systems. For imagining alternatives, though, directly setting flows is not intuitive: the most common way of thinking is rather to tune a set of parameters which represent levers of change (e.g. a population's average diet). These parameters are in turn translated into flows, which are subject to constraints. Parameters must be reconciled in order for flows to meet the constraints.

In practice, the economy is depicted as an arrangement of production and consumption activities. These are classified in categories, agriculture, construction etc. on the production side, and housing, mobility, diet etc. on the consumption side. For each category, several modes are possible (e.g., organic/conventional farming, vegetarian/meat diet). Each mode is represented by a unit production function describing the relationship between inputs (factors of production) and outputs. Finally, biophysical constraints are applied to the system (mass conservation, constraints on resource use, on pollution etc.).

The user provides: (i) level of population (ii) percentages of each mode inside each category (these are the model's parameters), (iii) how important these percentages are for him/her (relative weight). Since the input set of parameters usually does not meet the constraints, they need to be reconciled and this is what our prototype does.

Another way of exploring biophysically feasible alternatives consists of setting parameters one-by-one and at each step computing the option space for the remaining parameters.

Parameter reconciliation raises mathematical questions linked to the optimization problem. In particular, we study the consequences of choosing absolute vs. relative (%) parameters to depict the same alternative and show that these options lead to different results. Furthermore, this way of framing the problem, i.e. using production functions, is common in serious games related to resource management. In that context "reconciliation" is done manually and the solution space is discrete. For the moment, however, we only consider continuous option spaces.

After a brief presentation of the theory, we will focus on two illustrative examples. The first one pertains to nitrogen flows of the French agri-food system (Billen, 2018). Feasible alternatives show trade-offs between water quality, level of autonomy, export capacity, type of farming, and diet. The second example is a toy model of a whole economy, in order to illustrate feedback loops between sectors depending on multiple resources and generating multiple pollutions/wastes subject to thresholds.

Estimating dissipative losses in thermal spray applications: The current status and circular economy recommendations

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 15:45: Advances in MFA methods 2 (B0.17 KOG)

Mohamad Kaddoura [1], ***Guillaume Majeau-Bettez*** [1], ***Ben Amor*** [2], ***Manuele Margni*** [1]

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Thermal spray, which is a family of surface engineering technologies, is necessary in order for various components to meet technical functionalities under harsh environmental conditions. A thin coating material with the desired properties is applied to the substrate of the component to protect it. This technique comes at the expense of dissipative losses of coating materials throughout the life cycle of components. Some of those materials are considered critical due to their high economic importance, limited availability of viable substitutes, and supply risk. Measuring the share of these material life-cycle losses, which are usually high, has so far retained little attention in literature despite an abundance of parameters and characteristics of thermal spraying processes based on lab results. Accordingly, having a structured way to estimate the dissipative losses is needed.

This study applies substance flow analysis of the main metals used in thermal spray (Cr, Co, Mg, Mo, Ni, W, Y and Zr) to quantify their life-cycle dissipative losses. The investigated sectors are transportation (vehicles and aircrafts) and energy (gas turbines, hydropower plants and biomass plants) where thermal spray is highly utilized. Due to the scarcity of primary data, we strongly relied on experts' knowledge to balance mass flows of coating materials over the components' life cycle. This is complemented with an uncertainty range based on the pedigree matrix to account for the variability. Building on those results, material efficiency strategies specific to thermal spray applications are recommended to reduce the dissipative losses.

Preliminary results show that the life-cycle stage responsible for most of the dissipative losses is the coating itself, where real deposition efficiencies communicated by experts were much lower than what is usually reported in literature. Significant dissipative losses also occur at the end-of-life, where most coating materials are melted with the substrate (non-functional recycling) and not separated beforehand. Losses that occur during the use phase (e.g., by wear or corrosion) are negligible. Improving the deposition efficiency, recovering the unstuck coating and de-coating the components at their end-of-life were found to be key areas of intervention to reduce the critical material losses.

The parametrized framework provided in this study could be a basis to estimate the dissipative losses from other surface engineering technologies in the future.

LCA case studies 3

The Social Structure of Technology: Exploring the Potential of Social Accounting Matrices for Social Life-Cycle Analysis

Monday, 3rd July - 15:00: LCA case studies 3 (C0.06 KOG)

Carlos López-Morales [1], *Miriam Boyer* [2]

1. El Colegio de México, 2. Humboldt Universität zu Berlin

This paper explores the possibilities of social accounting matrices (SAMs) for contributing to social life-cycle analysis (S-LCA). Our objective is twofold: First, to explore the methodological advantage of combining Industrial Ecology's interest in social impacts with Input-Output Economics' capabilities for social accounting. Second, to explore the conceptual advantages of combining Input-Output's attention to physical aspects of technology as structuring an economy with the attention to technological structures as manifestations of particular socioeconomic and sociopolitical relations, as treated in Critical Studies of Technology, as they can be captured quantitatively by SAMs. The paper thus advances a technological model that offers, theoretically and methodologically, a more adequate understanding of the social structure of technology, as a process and an outcome, within an economy-wide scope.

S-LCAs have been developed with the objective of assessing the social impacts of goods and products across their life cycle, while SAMs have developed to describe the generation and distribution of income within an economy. Notwithstanding their specialized contexts, we observe the potential for common ground: Methodologically, under current guidelines, the social aspects analyzed in S-LCA include working conditions, health and safety, human rights, or cultural heritage, whereas the relevant agents include workers, local communities, consumer, and other agents placed at different stages of a supply chain. Given their economy-wide perspective, these impacts and agents can in principle be included in the construction of a SAM. This is because the latter not only includes the technological structure of an economy like an input-output table would do, but also describes the interactions between technologies, factors of production (i.e., labor and capital), and the institutions to which they associate (i.e., firms and households). Conceptually, moreover, SAMs allow us to conceive of technology not only as physical stocks that structure and economy but also to capture the social actors and institutions that reproduce the technological structure in the economy.

This type of combination of methods, scopes and concepts is not uncharted territory for industrial ecology nor input-output economics: past collaboration yielded hybrid-LCA, or the utilization of input-output databases for life-cycle analysis. In this paper, we ask whether the time is ripe for exploring a new interaction, this time motivated by industrial ecology's interests in social impacts and the input-output's capabilities for social accounting. In particular, we explore whether an expansion of hybrid-LCA to include the variables and accounts defining social accounting matrices is possible. To do so, we first trace the history of hybrid-LCA as a combination of lyfe-cycle thinking with input-output tables, then report on the connections of the latter with social accounting matrices, and finally see with the aid of numerical examples whether a SAM expansion to hybrid-LCA is possible.

The increasing presence of S-LCA in the literature indicates that the move to include social impacts into the understanding of products and technologies is necessary and relevant. Assessments of recent practice suggest the need of further explorations to develop consistency in the definition and quantification of "social inventories," along with the definition of analytical boundaries and scales. Similar to input-output tables, SAMs work both as an economic model (in this case, of income distribution) and as a database (depicting the circular flow of income), and we investigate on how their economy-wide scope and consistent methods can be of use for further development of S-LCA.

Social Life Cycle Assessment of formal and informal waste collectors using UNEP/SETAC guidelines - a case study in Uttara, Dhaka

Monday, 3rd July - 15:15: LCA case studies 3 (C0.06 KOG)

AZAD ASHRAF [1], ***Eugene Mohareb*** [2], ***Maria Vahdati*** [2], ***Elina Adam*** [1], ***Sruthi Udayakumar*** [1], ***Rohail Tahir*** [1]

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Municipal solid waste (MSW) generation is expected to increase worldwide by roughly 70 percent to 3.4 billion metric tonnes by 2050. Although sanitary waste management with resource recovery is targeted globally, more than half of waste in fast-developing regions still ends up in open dumps (World Bank, 2018). Developing countries like Bangladesh, which are undergoing rapid urbanization and population growth, face unique municipal solid waste management challenges; increasing levels of waste generation related to urbanization are going unaddressed due to the lack of allocated funds and insufficient organization. As a result, informal waste collectors play an important role in aiding waste collection and recycling in Dhaka. This study aims to assess the social life cycle assessment (SLCA) of formal and informal waste collectors in Uttara, Dhaka City, using guidelines established by UNEP and applying the latest impact assessment methodology.

In this study, workers (formal and informal) were the focal stakeholder group for assessment across four impact categories: working conditions, human rights, health and safety, and socio-economic repercussions. There were eight subcategories and 17 indicators for assessment within these four impact categories. A quantitative and semi-quantitative questionnaire was developed. SLCA in this case study applied a positive and negative indicator scale (from 0 to 0.9) to assign inventory scores to the survey answer percentage.Positive indicators (e.g., % sufficient salary) with lower prevalence were assigned higher scores, whereas the opposite score approach was taken for negative indicators (e.g., % child worker). The questionnaire was completed by 23 formal workers and 29 informal workers.

The results indicate that there is no marked difference of “Child Labour” subcategory between formal and informal waste collection sectors in Uttara, and that the “Gender-Based Discrimination” subcategory against female waste employees and for the overall “Human Rights” impact category scored relatively higher. A medium score of “Working Hours” subcategory indicates that both types of waste workers face overwork or exploitation. In the “Fair Salary” subcategory, informal workers have medium expectations for fair wages while formal workers have extremely low expectations. The overall “Working condition” impact category scored in formal worker category higher (negative impact) than informal worker since they work more external jobs and can earn more money. In addition, informal waste collectors are exposed to more health risks, with a negative social impact when comparing to the formal sector in “health and safety” category. The overall “social benefits” subcategory scored the same for both sectors. Furthermore, both sectors scored very high in the subcategory “social security” (I.e., extreme negative impact), indicating that both types workers face a serious lack of social security and no differentiation between the two sectors. Implementing solutions to these problems will support healthier and more hygienic waste sector, as well as enhancing knowledge and improving the social stability of this sector.

The full picture: Life cycle assessment of Norwegian household MSW generation - Impacts and potential environmental benefits of the complete waste management system

Monday, 3rd July - 15:30: LCA case studies 3 (C0.06 KOG)

***Kim Rainer Mattson* [1], *Johan Pettersen* [2]**

1. Norwegian University of Science and Technology, 2. Norwegian Univ. of Science and Technology

Municipal solid waste (MSW) generation and management has received increased attention the last decade, especially in connection to topics central to the overarching theme of circular economy. The Norwegian waste sector is often put forward as representative of a waste management system (WMS) with high collection and recovery rates. There has however, not been any systematic mapping and assessment of the combined environmental performance of the multiple downstream treatment chains for MSW. A significant information gap exists for assessing the effects of the whole WMS, and consequently for choosing strategic policies to address inefficiencies and/or poor environmental performance.

In this study, household waste generation, its handling, and downstream treatment has been mapped, representing a highly detailed overview of the waste management situation in Norway between 2017 – 2021. The complete treatment of the waste generated has been assessed with the EASETECH life cycle assessment (LCA) software, indicating the potential environmental damages and credits from replacing primary production of materials or energy.

The study draws attention to multiple important aspects of LCA modelling, namely 1) the sensitivity of techno-economic parameters for environmental performance, for instance, sensitivity ratio of heat recovery on climate change impacts, and uncertainty of different treatments, 2) the choices of life-cycle inventory data for treatments and substitutions, and 3) regional differences in the performance of the system. Since regional conditions can alter key aspects of waste flows, i.e., divergent treatment options compared to the average country level solutions, increased transport distances, use of treatments that under or over perform compared to benchmarking etc., including this in the assessment further highlights the importance of spatial considerations when performing LCA.

The study highlights considerable sensitivity and uncertainty of different treatments for municipal solid waste, and their potential environmental benefits. First, we show the main system drivers for emissions in the Norwegian waste management system and the resulting downstream treatment chain. We see the significant contribution of recycling and recovery efficiencies of the most common technologies for waste treatment, based on recent literature reviews and LCA studies. Secondly, we assess the importance of the assumptions made regarding what type of primary production is replaced with the product output of the Norwegian WMS. Showing that assumptions on material and energy substitution can generate large divergence of results. Thirdly, we show the importance of addressing regional differences in waste management practice, looking at the WMS of a metropolitan area (Oslo), a medium size city (Ålesund), and a rural area (Verdal). The sorting scheme and subsequent downstream treatment chain show different management practices and technologies in use, and how these influence the potential environmental impacts generated. The results of the spatial explicit LCA are contrasted with the LCA results of the country level WMS.

The findings are important for both policymakers and practitioners of waste specific LCA research and analysis. It gives clear indications of where the largest potentials for improving the Norwegian waste management system are situated at a national level. It also shows the importance of adapting the LCA study to regional conditions when addressing the system at the regional level. We highlight the significance of getting «the full picture» when designing waste management systems.

Future greenhouse gas emissions of sodium ion batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Monday, 3rd July - 15:45: LCA case studies 3 (C0.06 KOG)

Shan Zhang [1], ***Åke Nordberg*** [1]

1. *Swedish University of Agricultural Sciences*

Battery technologies play an vital role in the transition to a fossil-free society. Sodium-ion batteries (SIBs) are attracting significant attention as promising energy storage alternatives to lithium-ion batteries, due to abundant reserves and low cost of sodium. The environmental impacts of SIBs have been studied by several life cycle assessment studies. However, there is a lack of study to analysis future environmental impacts of SIBs, with considering the changes in the background system in the future. This study aims to conduct a prospective life cycle assessment to estimate the future GHG emissions of cell production in 2030, 2040 and 2050. Three SIB technologies were studied: layered oxide cathode with hard carbon (HC) anode; polyatomic anion cathode with HC anode; and Prussian white cathode with HC anode. The future background system was molded using the integrated assessment model REMIND, in combination with the Shared Socio-Economic Pathway 2 scenario. To facilitate a fair comparison, all three battery cells were modeled as a classic 18650 form, using a bottom-up approach. The best available data (latest data) was used to model the cell dimension and battery cell production system. The focus of the study was on cell production, therefore, a cradle-to-gate system boundary was applied. A functional unit of 1 kWh cell capacity was used. To gain a better understanding of the environmental performance of SIBs, results were compared to that of lithium-ion batteries. In sensitivity analysis, the effect of different HC production methods on the results was analyzed.

Urban Metabolism

What does “urban metabolism” mean? A conceptual engineering approach

Monday, 3rd July - 15:00: Urban Metabolism (B0.25 KOG)

Nicola Bertoldi [1]***, Daniela Perrotti*** [2]

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As observed by Kennedy (2016), modern industrial ecology can be characterized as an interdisciplinary field dealing with three kinds of metabolisms and their interactions, i.e., industrial, socio-economic, and urban metabolisms. However, urban metabolism studies have emerged independently of industrial ecology and encompass other fields, which differ from industrial ecology in epistemological, methodological, practical, and institutional terms (Newell & Cousins, 2015). Moreover, disagreements between industrial ecology-inspired approaches to urban metabolisms and urban ecology-inspired ones have emerged in debates on the nature of the analogy underlying the notion of “urban metabolism” itself. Said debates have notably crystallized around the question of whether cities should be compared to “ecosystems” (Golubiewski, 2012) or to “(super-)organisms” (Kennedy, 2012). Therefore, although the concept of “urban metabolism” has played an increasingly prominent role in framing how different disciplines have studied the flows of materials, energy, substances, waste, and pollutants through which cities interact with the environment (Bahers *et al.*, 2022), its content remains opaque since it appears to depend on the context in which it is used. Nevertheless, how could it be possible to clarify the content of the concept of “urban metabolism” so as to make it more transparent and readily applicable across fields as diverse as industrial, urban, or social ecology?

Our contribution outlines an answer to this question by drawing on a branch of analytic philosophy known as “conceptual engineering” (Chalmers, 2020). Understood literally and dynamically, the label “conceptual engineering” applies to approaches attempting to improve concepts or words, which are conceived as representational devices aiming to attain some desired theoretical or practical effects. Such approaches are guided by a description of these concepts’ content or use and an assessment of their functional efficacy that is geared towards practical implementation. Borrowing Isaac, Koch, and Nefdt’s (2022) distinction between purpose, object, goals, and targets of conceptual engineering, we can characterize our approach to the concept of “urban metabolism” as follows. First, our overarching purpose is to enhance this concept’s interdisciplinary and transdisciplinary applicability by clarifying its content. Second, consequently, the object of our approach is precisely such content, which we can understand, based on a view of concepts as embodying the semantic contents of words or phrases (e.g., Peacocke, 1992), as the meaning of the term “urban metabolism” itself. Third, the goal we pursue to further the general purpose mentioned above is reconstructing said meaning by extracting it from a corpus of 100 documents representative of urban metabolism studies and selected through the analysis of a limited pool of relevant literature reviews and theoretical articles (e.g., Kennedy, Pincetl & Bunje, 2011). Fourth, we achieve our goal by targeting concepts cognate to urban metabolism. More specifically, we seek patterns of lexical co-occurrence in the abstracts of our selected documents – through a human-machine hybrid, semi-supervised approach – to build a layered semantic network capable of capturing the content of said concepts and thus expressing how the notion of “urban metabolism” operates, relative to other concepts, in the field of urban metabolism studies as reflected in our corpus. In conclusion, our conceptual engineering approach contributes towards establishing a transversal, overarching meta-framework that aims to systematize the foundations of urban metabolism studies while facilitating the dialogue between industrial, urban, and social ecology. This work is supported by the Belgian Fund for Scientific Research F.R.S-FNRS under Grant n° MIS-F.4536.22.

Integrating urban metabolism and smart cities technologies

Monday, 3rd July - 15:15: Urban Metabolism (B0.25 KOG)

Federica Geremicca [1], ***Melissa Bilec*** [1]

1. *University of Pittsburgh*

The rapid advancement of urbanization is leading to a shift in urban planning and the utilization of diverse data streams and models to aid in effective planning. The aim of this research is to explore the connections between urban metabolism and digital twin technologies to ultimately aid in sustainable and effective urban planning. In order to explore this connection, a digital twin of one existing building and the adjacent urban streetscape was constructed and used as a pilot model.

A building information model (BIM) was developed from existing two-dimensional drawings, architectural renderings, specifications, and terrestrial laser scanning. Material estimates and their replacements were from the BIM to understand the building urban metabolism and associated material flows. Next, a digital twin was developed in Unreal Engine software utilizing the data streams of weather, indoor environmental quality (particulate matter (PM), volatile organic compounds, relative humidity, temperature, lighting levels), electricity use, steam flow, and water use.

This study is the first step towards the full integration of diverse data streams into an urban metabolism analysis by using digital twin technologies to visualize the outcome of this study dynamically and spatially. A key outcome of this work was streamlining the process of diverse data streams in the digital twin architecture, including integrating dynamic urban metabolism results. We envision that this approach will be a valuable addition to the field of sustainable urban design and planning, as it aims to bridge the gap between urban metabolism analysis and urban design. Moreover, the adoption of such technology can help rationalize the data collection process towards its standardization.

Urban Bioeconomy: Mapping Organic Resource Streams and the Bio-Symbioses in Cities through Material Flow Analysis

Monday, 3rd July - 15:30: Urban Metabolism (B0.25 KOG)

Nan-Hua Nadja Yang [1], *Aidong Yang* [1]
1. University of Oxford

Globally, the ecological footprints of cities, which are accountable for the majority of the world's resource and energy consumption, are increasing rapidly along with the exponential urbanisation rates. While cities and nature have traditionally been seen as diametrical opposites, the concept of Urban Bioeconomy strives to bridge this gap and to transform cities into bioeconomy hubs that assimilate to nature and manage their bioresources more efficiently. The concept focuses specifically on the biological side of cities and can therefore be seen as the bioeconomic subsection of the more widely known Urban Metabolism research. As resource accounting is often only conducted on national levels, the comprehensive bioresource flow data within urban and suburban environments will be highly valuable to create a local resource strategy for a sustainable future city.

To identify Urban Bio-Symbioses, i.e., the synergies between different bioeconomic sectors, this work maps the different bioresource streams within cities. It does so quantitatively by using Material/Substance Flow Analysis methods. Oxford and Singapore have been chosen as case studies as they represent two contrasting types of cities amongst developed countries in terms of population density, local conditions and land area. With this approach, the following research questions have been answered: 'How, where and when do biological resources currently enter, function within and exit urban environments? How do the current systems perform against a set of environmental criteria?' The focus was on the bioresources of the food system, green infrastructure and organic waste system. 2019 has been chosen as the reference year because it is the most recent calendar year not affected by the global pandemic.

Between Oxford and Singapore, the Material Flow Analysis in this work shows that Oxford imports most of its food and barely processes its organic waste within the city. It relies heavenly on its surroundings as it is embedded in a rural county. While Singapore similarly imports almost all of its food, an increasing amount of urban food production could be quantified in Singapore with its aim of 30% food self-sufficiency by 2030. Potential synergies between urban food systems and organic biowaste have been identified, e.g., the valorisation of wastewater and food waste to biofertilizers for urban agriculture. The Substance Flow Analysis of nitrogen and phosphorus, which are mostly responsible for eutrophication or greenhouse gas (GHG) emissions, shows that the majority of these nutrients can be found in wastewater and its valorised products like the digestate cakes. Further investigation is being conducted for carbon and its related GHG emissions as well as biocomponents such as proteins, lipids and carbohydrates to assess further possibilities for synergies and value-added products.

This work is significant because it is, to our best knowledge, the first work that combines quantitative research methods on urban bioresource flows and their nutrient flows with the lens of identifying synergies between different bioeconomic components. In general, the concept of Urban Bioeconomy has been rarely academically explored although it gained traction among practitioners and policymakers significantly. To help identify Urban Bio-Symbiosis opportunities, this research about the current state of cities laid the ground for future work on optimisations and improvements, including novel resource processing technologies, enhanced nature-based solutions and effective urban agriculture practices, towards a sustainable, circular Urban Bioeconomy.

Teleconnections and spatial metabolic rifts in urban material circularity

Monday, 3rd July - 15:45: Urban Metabolism (B0.25 KOG)

Thomas Elliot [1], ***Marie Vigier*** [1], ***Annie Levasseur*** [1]

1. École de technologie supérieure

Global demand for resources currently exceeds Earth's carrying capacity. Representing a majority share of global resource use, and the associated environmental burdens, cities must address their overconsumption using systemic tools that incorporate material circularity. However, in order to do so, urban decision-makers must rely on robust measurement tools representing the complex dynamics of urban systems to guide their actions. This work explores the potential for the construction sector to reduce the indirect environmental impacts connected to materials, and the role that increased material circularity in the coming years. An urban metabolism simulation tool based on system dynamics modelling and life cycle assessment is deployed subject to growing material circularity to estimate the effects of a circular construction sector on indirect environmental impacts. Illustrating with a case study of Montréal (Canada), urban flows and their impacts are disaggregated to 160 supplier nations and 13 Canadian supplier provinces and territories. The results show around two-thirds of material tonnage is sourced provincially, where the major environmental impacts are generated. As material circularity increases over time, the simulations show decreases in the rest of Canada and rest of world impacts, with a higher portion allocated to the city of Montréal, due to the increased activities associated with end-of-life flows. However, these decreases are found to be shared mostly among Canada's more developed trading partners, revealing an environmental justice risk for circular materiality to disproportionally favour the better-off.

Complex supply chains and flows

Mapping the economic complexity of green supply chains

Monday, 3rd July - 15:00: Complex supply chains and flows (B0.31 KOG)

Yang Li [1]

1. *Harvard University*

As the world is transitioning into a more sustainable system of production and consumption, the booming demand of green products enables new developing opportunities, and many countries consider a deeper integration into the green supply chains as a national strategy.

However, the green supply chain represents a complex system of multiple products, which lack a view of its full landscape. Each green product requires specialized knowledge to gain comparative advantage in the global market, and the pathway to success depends on the place-specific portfolio of existing capabilities. In this work, 11 green supply chains were identified from research papers, reports and life-cycle inventory database, based on their physical input-output relations, and formed a network of 472 nodes and 588 edges, spanning the fields of renewable energy generation & storage, CCUS, green hydrogen, etc. Machine learning algorithms were used to match the identified products to 344 standard 4-digit HS products via their semantic similarity. The method of economic complexity and product space were further applied on the identified green products, which revealed the competitiveness of countries and the relatedness between products via their co-occurrence at country level. It was found that: 1) the identified green supply chain network is weakly connected and exhibits clear community structure for different fields, which accounts for a wide range (~20%) of all HS products. 2) The products involved in green supply chains mostly locate in the central of product space network, with a higher relatedness if there exist direct input-output relation, and when a pair of products belong to the same community, which indicates more shared production capabilities (e.g., shared labor and skill requirement/infrastructure/etc.) besides their shared supply chain features. 3) The involved products are mostly complex product in the category of machinery/electronics/chemicals, except the ores of critical minerals with low complexity. The green supply chain of semiconductors on average are most complex, followed by various renewable energy generation, while energy storage is less complex. Most countries with a high comparative advantage in exporting the involved products have a high economic complexity score and a diversified production structure. 4) Countries are more likely to diversify into the green products with many existing related products and shared capabilities, and almost half of the countries have the potential to diversify into at least 1 product involved in green supply chain. However, the probability shrinks quickly as more products are considered, which means only a few diversified countries like Germany and China could potentially have a comparative advantage along the whole green supply chain. Less-diversified developing countries need smart strategy to target their high-potential sectors and pay more effort to establish and maintain their advantage in green products.

In summary, the results of this analysis provide valuable insights into the structure of the green supply chain and its relationship with economic complexity, especially the significance of acquiring and developing the necessary knowledge and capabilities for effective engagement of the green supply chain.

Assessing Supply Risks and Unveiling Holistic Insights: A Comprehensive Analysis of the Global Nickel Supply Chain

Monday, 3rd July - 15:15: Complex supply chains and flows (B0.31 KOG)

Simone Della Bella [1]***, Burak Sen*** [2]***, Gang Liu*** [3]

1. SDU Life Cycle Engineering, Department of Green Technology, University of Southern Denmark, 2. SAU Center for Research & Development, and Applied Research (SARGEM) Faculty of Engineering, Sakarya University, 3. University of Southern Denmark

Nickel (Ni) is a mineral of significant concern for nations worldwide and plays a crucial role in the global green transition. The anticipated surge in demand for this strategic mineral is driven by the increasing need for low-carbon technologies and the widespread adoption of consumer electronics. While Ni is extensively utilized in alloys, the majority of Ni supply (class 2) is presently consumed by the global steel industry. However, recent years have witnessed a substantial rise in the use of Ni sulfate in lithium-ion batteries.

Existing studies on the Ni supply chain, including supply risk assessment, have primarily focused on Ni class 2 for the stainless steel industry, neglecting differentiation between various products such as nickel sulfate, Ni class 1, FerroNickel (FeNi), and Nickel Pig Iron (NPI). Moreover, these studies have exhibited limitations in system boundary definition and a lack of consideration for regional coverage.

To address these gaps, this study undertakes a comprehensive Supply Risk Assessment of the global Ni supply chain, encompassing the entire industrial chain network from mining to waste management. The study's objectives are threefold: to depict the present state of the Ni industrial chain, identify supply risks associated with Ni products, and evaluate import structures and risks at a multi-regional level for 2019. The study categorizes supply risks into four groups: upstream, middle-stream, downstream, and general risks, encompassing disruptions in mining, refining, manufacturing, consumption, and overall supply chain operations. By adopting this comprehensive categorization, the study provides a holistic perspective on supply chain risks and establishes a systematic analysis framework.

The study aims to evaluate risks at each stage of the nickel supply chain, identify vulnerabilities, and propose strategies for risk mitigation. Ultimately, the findings will contribute to a deeper understanding of supply chain dynamics and facilitate the development of effective risk management approaches for industries reliant on nickel.

Substance Flow Analysis of Pathogens for Epidemics Control

Monday, 3rd July - 15:30: Complex supply chains and flows (B0.31 KOG)

Gjalt Huppes [1], *Ruben Huele* [1]

1. Leiden University, CML

Substance flow Analysis is one main tool of Industrial Ecology. Examples cover metals and asbestos, partly airborne and toxic at inhalation. PM2.5 and UFPs (UltraFineParticles) of various compositions are airborne for various durations. Examples of short-lived substances are O3, NOx, SOx, and VOCs, and biotic substances such as viruses, bacteria, molds, and pollen. Airborne viruses have the size of UFPs, larger if in clusters. Their production in epidemics is mostly in humans. They may remain infectious up to hours, long enough for an epidemic.

Influenza and SARS-CoV-2 pandemics have shown a remarkable diversity in preventive approaches, mostly based on age-old but weak knowledge. As to sources, what are emission volumes; how do they develop with an infectious person; and what is the duration of infectiveness? As to transport, what is the nature of transport mechanisms; their decay rate; and their dilution rate? As to exposure, what is the amount required for infection; and what is the dangerousness of virus variants if infected, certainly related to the health state of the infected person and how deep viruses travel into the lungs? These uncertainties will still be high in coming epidemics and pandemics: they are the known unknowns. Preventive measures are taken under high uncertainty, quite unavoidably. However, Industrial Ecology can supply some relative certainties, based on Substance Flow Analysis. Mass balances must hold, also for viruses and other biota.

In an epidemic, there certainly is a source and infectious exposure. Production is a continuous process in the infected person, leading to emission and new infection. Concentrations can build up in confined spaces only, countered by decay and dilution. It is absent in open air. We model the unknown emission volume, using an index number equal for any virus type. The average emitting person starts at 100. We add an emission growth rate in a person, relevant for longer durations of stay. Emissions ends with effective countermeasures, as by antibodies in the body, by medicines, by confining emitters, or by death.

Situations can be typified as to: the concentration build-up resulting from an emitter; the natural virion decay; by dilution, as based on ventilation and filtering; and by the duration of stay of an emitting and an inhaling person. The analysis covers typical situations, such as for hospitality; shopping; home and care; working; and travelling. Their quantitative outcomes give an astonishing variation in the relative chance to be infected, by a factor of several hundreds.

These outcomes do not depend on the specific virus type circulating. Measures can focus on the situations with the highest virion exposure. General preventive measures relate to effective dilution, as by ventilation. Prevention during epidemics is by avoiding most dangerous situations and by using filtering systems. Seriousness of measures will vary between virus types, as soon as they are known. For Ebola, they are harsh, uniform, and binding. For the common cold, some persons will take precautions voluntarily, those most vulnerable. After build-up of immunity in the general population, as with influenza and now SARS-CoV-2, measures may focus on the vulnerable and on avoiding the most contagious situations. For any virus, general prevention by improved ventilation in high concentration places remains the main approach. Similarly holds for bacteria and non-biotic short-lived toxics.

Industrial Ecology for health: Dilution is the solution to any short-lived pollution.

Implementation of carbon pricing in an aging world calls for targeted protection schemes

Monday, 3rd July - 15:45: Complex supply chains and flows (B0.31 KOG)

Peipei Tian [1], ***Kuishuang Feng*** [2], ***Heran Zheng*** [3], ***Klaus Hubacek*** [4], ***Jiashuo Li*** [1], ***Honglin Zhong*** [1], ***Xiangjie Chen*** [2], ***Laixiang Sun*** [2]

1. *Shandong University,* ***2.*** *University of Maryland,* ***3.*** *University College London,* ***4.*** *University of Groningen*

Understanding the impact of climate fiscal policies on vulnerable groups is a prerequisite for equitable climate mitigation. However, there has been a lack of attention to the impacts of such policies on the elderly, especially the low-income elderly, in existing climate policy literature. Here, we quantify and compare the distributional impacts of carbon pricing on different age-income groups in the US, the UK and Japan and then on different age groups in other 28 developed countries. We find that the elderly are more vulnerable to carbon pricing than younger groups in the same income group. In particular, the low-income elderly and elderly in less wealthy countries face greater challenges because carbon pricing lead to both higher rate of increase in living cost among low-income elderly and greater income inequality within the same age group. In addition, the low-income elderly would benefit less than the younger groups within the same income group in the commonly proposed carbon revenues recycling schemes. The high vulnerability of the low-income elderly to carbon pricing calls for targeted social protection along with climate mitigation polices towards to an aging world.

Energy systems 1

Delivery of energy sustainability: Applications of the "STAR" protocol to the Sustainable Development Goal 7 index and its interaction analysis

Monday, 3rd July - 15:00: Energy systems 1 (B0.41 KOG)

Dandan Zhao [1], ***Olli Varis*** [1], ***Jialiang Cai*** [1], ***Lei Shei*** [2], ***Ayman Elshkaki*** [3], ***Junguo Liu*** [4]

1. Aalto University, 2. University of Chinese Academy of Sciences, 3. Chinese Academy of Sciences, 4. North China University of Water Resources and Electric Power

The establishment of Sustainable Development Goal (SDG) 7 within 17 SDGs of the United Nation 2030 Agenda operationalizes the discussion of how to tackle energy challenges for the delivery of energy sustainability. Few studies have yet produced composite indices to capture the multi-dimensional nature of energy development as well as a general and operational framework for the evaluation of countries' overall performance on achieving SDG 7 remains absent. This hinders the quantitative assessment of interactions between SDGs at the specific target level. To address this gap, with the application of the "STAR" (Straightforwardness, Transparency, Availability, and Readiness) protocol, a composite Sustainable Development Goal (SDG) 7 index was developed upon the SDG 7 targets and indicators to scrutinize global energy challenges, and the interaction analysis between SDG 7 and SDG 6 based on the 'STAR' protocol underlined the importance of co-evolution in the water-energy nexus. The profiles of the indicators and index by 232 countries and territories unraveled the global implementation baselines of the SDG 7 dimensions (energy services, renewable energy, and energy productivity). Several key findings can be drawn from the analysis:

A majority of countries are on track to achieve universal energy services by 2030, apropos of population having access to either electricity or clean fuels and technologies. Yet Sub-Saharan African countries need to substantially augment the implementation pace of service coverage.

- The $SDG7_I$ score differed considerably between countries and territories, 8.6% (20 out of 232) of the countries belonged to high levels, 34.1% (79 out of 232) were located at medium-high level, but the $SDG7_I$ values in more than 50% of the countries were lower than 50.
- 86% (67 out of 78) of the total interactions had interrelationships statistically, and the synergies largely outweighed the trade-offs relations, which accounted for 70% (54 out of 78) of the total. Among human development groups, the very high development group showed the biggest synergies both in the absolute value (36 out of 78) and in the shares (46.1%), while the medium and low development groups had the lowest synergies (19 out of 78, 24.4%).
- Significant positive correlations were detected either from an indicator or index perspective between SDG 7 and SDG 6, which demonstrated synergistic relations from SDG 7 can promote the achievement of cross-domain SDG targets.
- The "STAR" protocol has great applicability to (1) facilitating the evaluation of synergies and trade-offs between SDGs and their targets grounded in specific context with differential circumstances across the 2030 Agenda, (2) identifying the policy sensitivity of the SDG indicators for policy effectiveness assessment, and (3) fostering multi-level governance and collaboration to leverage synergies and resolve trade-offs.

Biogas potential studies: A review of their scope, approach and relevance

Monday, 3rd July - 15:15: Energy systems 1 (B0.41 KOG)

Natasia Angel Setiawan Tjutju [1], ***Jonas Ammenberg*** [1], ***Axel Lindfors*** [1]

1. Linköping University, Biogas Solutions Research Center

A significant amount of fossil energy is to be replaced by renewable sources in the short-term future and biogas can play an important role in this transition by producing renewable energy and biofertilizer from anaerobic digestion of organic waste. Thus, biogas can contribute towards combating climate change while enabling nutrient recycling and effective organic waste management. Furthermore, biogas can be a complement to other intermittent renewable alternatives, such as solar and wind power, which can improve energy security and flexibility. To understand the relevance of biogas solutions and support their development, biogas potential studies are commonly used to assess available biomass resources and possible biogas conversion pathways within a specific geographical boundary. Within this area, several potential studies exist and different methodologies are applied, which results in a large heterogeneity. Regarding bioenergy potential studies in general, several literature reviews have been conducted with the aim of highlighting critical methodological assumptions, assessing the methodological transparency of the studies and discussing their comparability. When it comes to biogas potential studies, however, such reviews are missing. Conducting this type of methodological review of biogas potential studies is a complement to the general bioenergy potential reviews since these general studies cannot capture the particularities that are specific to biogas potential assessments. Therefore, in this study, existing biogas potential studies are systematically reviewed. The review covered 98 geographically-bounded potential studies published in scientific literature and focused on the following methodological aspects: the geographical scope of the studies, the type of potential that was estimated (e.g., theoretical, technical or socio-economic), the feedstocks included in the studies, the methods applied to estimate potentials, the outputs covered by the potential study (e.g., biogas, biofertilizer or carbon dioxide) and if the studies applied any uncertainty management approaches. The review showed that there are very few studies that estimate all outputs of biogas systems, as biofertilizer and carbon dioxide amounts are commonly not estimated. Moreover, very few studies applied uncertainty management methods in their analysis, indicating a need for methodological development in this area. In general, most studies applied a static modelling approach, which is based on linear relations between demographic, agricultural and industrial characteristics and the availability of biomass from municipal, agricultural and agri-food industrial waste, respectively. There are several critical elements that significantly affects the outcomes of the study, such as the selection of substrates and conversion factors. Furthermore, many potential studies have challenges in relation to transparency and lack a systematic approach to deal with uncertainties. Based on the observed challenges, the review includes recommendation on how to improve biogas potential studies to increase accuracy and relevance.

Towards a circular green hydrogen supply chain: a fieldwork research

Monday, 3rd July - 15:30: Energy systems 1 (B0.41 KOG)

Pamela Salinas-Velarde [1]***, Ruth Carrasco-Gallego*** [2]***, Alberto Abánades*** [3]

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The development of the green hydrogen (GH) industry is reaching global momentum as the demand for this technology increases, particularly in the European Union (EU). The EU GH supply chain is being strongly accelerated due to the current geopolitical situation and the energy transition towards sustainable alternatives to fossil fuels to achieve decarbonization goals. This energy transition should involve not only an energy perspective, but also other aspects like the preservation of resources value (circular economy), and the design of a GH supply chain aligned with the principles of a regenerative and restorative economy. This calls for the need to broaden the analysis considering the impacts of the equipment used throughout the GH supply chain and use this information as feedback in the design phase accordingly. In effect, this lack of circular design perspective has posed significant and current end-of-life challenges in other renewable energy generation technologies, such as wind and photovoltaics (PV). According to Martinez-Marquez et al. (2022) and Farrell et al. (2020), by 2050 there will be 60-78 million tons of PV waste and around 42 million tons of composite waste from wind turbine blades that will need to be treated annually worldwide. However, the up-to-date approach in the scientific community regarding the design and conceptualization of the new green hydrogen supply chain, to the best of our knowledge, still follows the mainstream linear standpoint approach (Correa et al., 2022; Sgarbossa et al., 2023).

To fill this gap, in this study, we evaluate the current GH supply chain in the EU from a circular economy perspective and identify which opportunities and barriers exist for implementing a circular supply chain in this sector. The analysis will be based on primary data gathered from visits to already installed and operational GH facilities in Spain and interviews with hydrogen experts, facilitated by the fact that this research is framed in an industrial Ph.D. program with Iberdrola, the top European private electricity utility in industrial R&D investment (CEU. JRC., 2022). A first focal point is to explore which end-of-life and recycling pathways for electrolysers described in the literature are already set in place and whether they ensure sufficient recovery flow to reduce the dependence on primary raw materials, especially critical materials. For instance, the manufacturing of Proton Exchange Membrane Electrolysers requires the use of critical primary materials such as platinum, iridium and scandiumm (Kiemel et al., 2021). This poses a bottleneck risk for the entire GH supply chain due to possible material scarcity during the expected electrolysis scale-up period (2020-2050). Similarly, it has been reported that around one percent of the fuel cell assemblies occur in the EU (European Commission, 2020), which constitutes another bottleneck to producing GH within the EU borders. Another focal point will be to investigate which other CE strategies are being implemented within the GH supply chain, and how the implementation of CE strategies at the supply chain design phase could prevent a situation like the one faced by wind and PV technologies . The impact of current regulatory framework and technology maturity of material recovery technologies in the GH sector will also be part of the study.

Acknowledgements

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Carbon Tax Design and Revenue Recycling in Line with National Redistribution Policy and Global Justice Principles

Monday, 3rd July - 15:45: Energy systems 1 (B0.41 KOG)

Xiangjie Chen [1], ***Daniele Malerba*** [2], ***Kuishuang Feng*** [1], ***Yannick Oswald*** [3], ***Klaus Hubacek*** [4]

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Carbon taxation is regarded as an essential tool for curbing carbon emissions but can be regressive, in the worst case increases poverty, and moreover lacks universal acceptance among the public and policymakers. Recycling the tax revenue raised to vulnerable households is a promising solution to this issue. However, little is known about the best strategy for designing such a policy at the global level. By using an environmentally extended global multiregional input-output approach based on the Global Trade Analysis Project, a highly detailed expenditure database and data on coverage of social assistance programs, this paper investigates the effectiveness of various carbon taxation methods and revenue recycling mechanisms in reducing poverty and inequality between and within countries. We find that the policy mix with the highest poverty reduction potential is implementing a consumption tax with higher tax rates on luxury goods and recycling revenue through the expanded social assistance systems during the COVID-19 pandemic. While differentiating tax rates across goods within countries is advantageous, the average tax level across countries is best kept uniform since it potentially offers governments in low- and middle-income countries more financial capacity to support the poor. Furthermore, collecting a global climate fund from developed countries and redistributing it to developing countries based on poverty headcounts can further significantly reduce poverty and inequality within and between countries. However, substantial improvements in social assistance systems are urgently needed to further unlock the poverty-reduction potential of revenue recycling, particularly in Sub-Saharan African countries. Also, recycling carbon tax revenues to combat poverty and inequality will inhibit the emission reduction effect of carbon taxation in the short term, necessitating additional mitigation efforts in other areas.

Social Dimensions 2

Status of Smartphone Garbage Applications Provided by Japanese Local Governments

Monday, 3rd July - 15:00: Social Dimensions 2 (B0.16 KOG)

Seiji Hashimoto [1], *Riki Yukawa* [1]

1. Ritsumeikan University

Many local governments in Japan have introduced smartphone garbage applications (apps) in recent years because of various difficulties in taking out household garbage, such as mistakes in confirming garbage collection dates, forgetting to take out garbage, and not knowing how to put out or separate garbage. For this study, we surveyed the functions provided in current garbage apps and examined functions that residents regard as convenient and necessary, the actual access status to each function. We further analyzed the intentions and effects of introducing garbage apps by local governments. We conducted an internet survey of garbage apps, a questionnaire survey of residents, an access log analysis to each function, and an interview survey of local governments. Results indicated the followings: (1) About 20 garbage app functions were identified, among which 'monthly calendar', 'weekly calendar', 'garbage disposal day notification', 'garbage disposal method list', 'garbage sorting dictionary', 'news', 'FAQ', 'government office contact information', 'related business contact information', and 'regional setting change' functions were installed in most local government garbage apps. (2) Many people reported 'monthly calendar', 'weekly calendar', 'garbage disposal method list', and 'garbage separation dictionary' functions as convenient. 'Garbage sorting dictionary', 'garbage disposal method list' and 'news' functions were the most frequently accessed. Few responses indicated the 'news' function as convenient, but it was used frequently. (3) The adoption rate of the 'oversized garbage application' function is not high, but it was highly demanded and is needed by residents. Requests were also made for a payment function for oversized garbage charges and a function for listing charges. (4) The operational effects of local governments after introducing the garbage apps include reduction in telephone inquiries, easier information transmission to residents, reduction in inappropriate discharges, increased awareness of garbage reduction, and improved convenience of garbage disposal.

Towards linking social metabolism with the behaviour of individual agents

Monday, 3rd July - 15:15: Social Dimensions 2 (B0.16 KOG)

Raphael Asada [1]***, Julia Wenger*** [1]***, Claudia Mair-Bauernfeind*** [1]***, Michael Kriechbaum*** [1]***, Tobias Stern*** [1]

1. *Institute of Environmental Systems Sciences, University of Graz, Austria*

Socio-metabolic system states can be seen as a direct outcome of utilizing production technologies to meet needs and wants that are contingent on our lifestyles. The extent to which historical and hypothetical adoption of technologies and lifestyles affect(ed) socio-economic metabolism has been studied at the system level (e.g., Cao et al. 2018; Vita et al. 2019), but references to individual behaviour are largely absent (Haberl et al. 2019). A promising way forward could be to strengthen the integration of socio-metabolic research and agent-based modelling of innovation-diffusion to better understand emergent phenomena that arise from micro-level interactions of relevant decision-making entities and alter the global socio-metabolic system. Agent-based models are particularly well-suited to study societal change, as they can be used to represent emergent system properties, non-linear behaviour, diversity and heterogeneity, and other characteristics of sustainability transitions (Köhler et al. 2018). Sustainability-related ABMs frequently place a focus on the diffusion of technologies and lifestyles and the conditions and mechanisms that foster or hinder such diffusion processes (Castro et al. 2020). Using a specific example, this contribution explores micro-level behaviours that may play a major role as drivers of change in global socio-metabolic patterns and associated environmental effects. To this end, the adoption process of an alternative energy storage technology is modelled at the level of individual agents, in which an electrolyte in conventional vanadium-based redox flow batteries is replaced by a lignin-based (Schlemmer et al. 2020) one. To achieve this objective, we use, first, a descriptive formalization of the relevant market actors embedded in social networks whose interactions generate emergent dynamics (Wenger et al. 2023, submitted). The agent-based model consists of both deterministic and probabilistic decision rules and is empirically grounded in techno-economic studies and trade and market data. Second, we compile technology vectors that contain empirical data on the use of natural sources and sinks, products, and labour and capital services that result from the production of an output unit using the technologies and lifestyles involved. The data is sourced from multi-regional input-output databases, life cycle inventories, techno-economic studies, and trade and market information. Third, we integrate a multi-regional input-output model (Stadler et al. 2018) with the agent-based model using the technology vectors as link elements. A sensitivity analysis encompassing the integrated socio-metabolic agent-based model is conducted to determine and characterize model behaviors resulting from varying parameter settings and their impact on social metabolism.

The approach is expected to provide a way to study local foreground contexts on the micro scale, taking into account the complexity and detail of the subject matter without losing sight of potential system-wide effects. The contribution will show how system structures of socio-economic metabolism can be modelled as entities that emerge from behavioural dynamics at the level of individual agents and where the difficulties of such an endeavour lie. At the conference we will present first results and discuss the usefulness of the approach for socio-metabolic research.

[List of references available upon request]

Impacts of working arrangements and lifestyle factor importance on environmental consciousness

Monday, 3rd July - 15:30: Social Dimensions 2 (B0.16 KOG)

Andrew Chapman [1], *Shamal Karmaker* [2], *Yosuke Shigetomi* [3]

1. Kyushu University, 2. University of Dhaka, 3. Nagasaki University

This research investigates the impacts of people's demographics, preferred working arrangements and utilization of their free time on environmental consciousness. Such an investigation is timely due to the changing expectations around working, and the rising popularity of work-from-home arrangements leading to increased flexibility. Although the linkage between income and environmental impact is well understood, the mediating factors between working arrangements and environmental concern is to date unclear. Through the analysis of a nationally representative survey conducted in Japan, we clarify people's desire to work shorter hours, subject to the maintenance of income levels, along with a desire to consider revised working arrangements if environmental improvements can be anticipated as a result. One important finding of this research is that those who prioritize their free time for family and friends have a much higher probability of valuing the environment and thus reducing their carbon footprint. These findings have implications for policy design which encourages low impact working arrangements, the sharing economy and a family friendly society. Further, in terms of implications for industrial ecology the findings of this research will provide suggestions for the reduction of footprints in line with stakeholders identified behavioral and environmental preferences.

The Status and Trend of Indonesian Provinces' Sustainability: A Genuine Savings Approach

Monday, 3rd July - 15:45: Social Dimensions 2 (B0.16 KOG)

Viktor Pirmana [1], ***Armida S. Alisjahbana*** [2], ***Arief Ansory Yusuf*** [2]

1. Padjdjaran University, 2. Padjadjaran University

Indonesia is known as one of the countries in the world blessed with abundant natural resources. Thus, a sustainable development indicator is needed to show whether Indonesian development is sustainable or not. This study aims to assess the province's pattern in Indonesia concerning the sustainable development aspects using genuine savings indicators for 2005 and 2016. Genuine savings is the actual saving after adjusting for the depletion of natural resources and pollution damage. Based on the findings, the Indonesian sustainable development profile has improved from 2005 to 2016. The increase in genuine savings value during that period reflects this improvement. Almost all Indonesian provinces contributed to this improvement. Exceptions are Papua, East Kalimantan, and South Kalimantan. The sustainability of these three provinces is relatively vulnerable as they rank low in terms of the ratio of genuine savings to GRDP. The analysis calls for the need to diversify economic activity not too dependent on the extractive and pollute sectors as well as increasing productivity so that for each unit of the liquidation of natural assets, we can generate welfare as much as possible.

Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (part 2)

An analytical framework to assess circular action contributing to climate change mitigation

Monday, 3rd July - 16:30: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (part 2) (C1.31 KOG)

Oreane Edelenbosch [1]***, Detlef van Vuuren*** [2]

1. Copernicus Institute Utrecht University, 2. PBL Netherlands Environmental Assessment Agency

session: BRINGING INDUSTRIAL ECOLOGY AND THE CIRCULAR ECONOMY
INTO INTEGRATED ASSESSMENT MODELS

Current climate policy worldwide still fails to reach the rapid decarbonisation rates required to implement the goals of the Paris Climate Agreement by a wide margin. The potential for GHG emission reductions via circular economy (CE) and material efficiency strategies has been highlighted in several recent scientific publications and is increasingly appreciated by policymakers. CE could address the primary production of several materials associated with high emission footprints, which are relatively hard-to-abate and as such complement other climate policies related to energy efficiency and decarbonisation. Given the required speed of emission reduction and challenges in difficult-to-decarbonise sectors, understanding how CE strategies can contribute to mitigating emissions is rapidly needed.

Currently model-based analysis of climate change mitigation lack proper tools to evaluate the impact of future material use along with the contribution of various CE strategies and policies on GHG emission mitigation. The core reason is that they do not consistently depict material stocks and circular flows such as recycling or re-use. For example, model-based analysis currently cover industrial emission reductions by 1) increasing energy efficiency (e.g., more efficient steel making) and 2) using low-carbon energy sources (e.g., using renewable energy in steel making), but not by 3) looking into strategies for reducing the production of primary materials (e.g., less steel).

The EU-horizon CIRCOMOD project aims to address this by developing a new generation of advanced models and model-based scenarios that consistently represent the stocks and flows of materials through the economy and considers the impact of CE strategies along the whole life cycle. CE strategies are typically studied from different perspectives, including economics, material flow analysis, life cycle assessment, climate mitigation models, environmental impact analysis and behavioural sciences. A first step crucial step will be developing a full analytical framework to build a logical understanding of the main CE mechanisms and support information exchange between these different disciplines and research communities. The analytical framework will encompass a systemic perspective on how material flows interact with the socio-economic system, energy and land-related systems, and the climate system.

The project builds on expertise of different modelling communities, including industrial ecology and material flow modelling, macro-economic modelling, and more process-oriented integrated assessment models. The use of multiple models will allow to consistently analyse connections between material production, the overall economy, and the environment including 1) the connection of materials to the economy through the products and services they provide, as well as the capital and labour they require; 2) how the consumption of materials can lead to resource scarcity and waste generation, and 3) the substantial amounts of energy and land needed to produce and use materials, contributing significantly to climate change. This emphasis on dynamic models will allow to go beyond existing analytical frameworks that are typically focussed on the effects of individual circular economy measures towards assessments that incorporate rebound effects, economic spill-overs, and potential socio-economic feedbacks.

The analytical framework will serve as a guide to map knowledge gaps, organize model improvement efforts, and identify opportunities for exchanging between each of the three modelling communities. For example, Integrated Assessment Models may provide scenario data on long-term product demand, enabling the assessment of resulting economic feedbacks through the application of Macro-economic models, thus strengthening the development of consistently integrated scenarios.

The role of chemicals in the transition towards a low-carbon and circular society: an integrated assessment modeling approach

Monday, 3rd July - 16:45: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (part 2) (C1.31 KOG)

Gamze Unlu [1], *Florian Maczek* [1], *Jihoon Min* [1], *Volker Krey* [1]

1. International Institute for Applied Systems Analysis

Chemicals are fundamentally integrated into our daily lives with various uses ranging from packaging, clothing, and electronics to fertilizers. The stocks of modern society such as energy infrastructure, buildings, or vehicles also depend on the production of these materials. The chemical sector is one of the largest energy-consuming industries heavily depending on oil and gas. It is the third largest emitter in the industry amounting to 18% of all industrial-sector CO2 emissions (IEA, 2018). The carbon contained in chemical feedstocks is locked into final products until it is released at the end of lifetime when the products are burned/decomposed. Therefore, the whole life cycle of the chemicals including production, use, and disposal poses variety of sustainability challenges. The production of “primary chemicals”, namely High-Value Chemicals, ammonia, and methanol together account for two-thirds of the total energy demand in chemical sector (IEA, 2018).

Demand for chemicals is surging with the growth in stocks and consumption. There is feedback between chemical production (and the resulting emissions) and some circularity/climate mitigation strategies in end-use sectors. Most notably, strategies in the building sector such as wood-based construction or building retrofits with increased insulation require more intense use of the two important primary chemicals: methanol and plastics. Similarly, the trends in transportation have connections with plastic consumption as the sector constitutes 7% of the plastics demand (Geyer et al., 2017). In addition, chemical production has a link with agriculture as ammonia production is the biggest contributor to sectorial emissions. With over 70% of ammonia used in fertilizers, fertilizer demand reduction strategies have impacts on chemical production.

In this study, we develop an extended representation of the chemicals sector, and the resulting material flows in MESSAGEix-Materials, a module that represents the material cycles from production to the end-of-life stage within the MESSAGEix-GLOBIOM Integrated Assessment Modeling framework (Krey et al., 2020). The chemical sector in MESSAGEix-Materials is extended to represent circular options (e.g., recycling in plastics), low-carbon technologies (e.g. CCS), and a variety of feedstock alternatives that the sector needs for an urgent transition. A scenario study is designed to investigate alternative decarbonization pathways in the chemical industry and the feedback with the circularity/mitigation measures from the end-use sectors. The assessment in the construction sector reveals that the positive effects of substituting concrete and steel with structural timber could be diminished by the increased adhesives demand. For agriculture as an end-use sector, with the coupled GLOBIOM land-use emulator, the implications of targets defined in the Sustainable Development Goals on fertilizer demand are assessed. The respective SDG targets include, inter alia, dietary changes, and food waste avoidance. Preliminary results show a 25% reduction in ammonia demand in 2050 compared to a baseline scenario. For the transportation sector, our scenarios reveal that vehicle stock with shared mobility can decrease up to 98% in 2050 with a significant effect on the reduction of materials use (e.g. between 56% and 90% reduction in steel demand). This analysis can be further extended to the plastic demand of the sector.

We conclude that it is important for IAMs to represent material flows more explicitly to be able to observe different dynamics between the industry decarbonization and the mitigation/circularity strategies in the end-use sectors such as buildings, transport , and agriculture. The chemicals industry is one example where demand-side dynamics play an important role.

Representing battery value chains for electromobility in MESSAGEix-Materials-Transport. Towards improved integration of industrial ecology data in IAMs.

Monday, 3rd July - 17:00: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (part 2) (C1.31 KOG)

Lorenzo Usai [1]***, Anders Hammer Strømman*** [1]***, Gamze Unlu*** [2]***, Jihoon Min*** [2]***, Volker Krey*** [2]

1. NTNU, 2. International Institute for Applied Systems Analysis

Abstract belonging to a proposed special session named: Bringing Industrial Ecology and the Circular Economy into Integrated Assessment Models

The Industrial Ecology field has recently been widely applied in the evaluation of the transition to electromobility and the potential challenges and trade-offs coming from the deployment on a global scale of Li-ion batteries used in electric vehicles. In this context, Material Flow Analysis (MFA), used for understanding potential raw materials bottlenecks, and Life Cycle Assessment (LCA), applied for evaluating the production and recycling impacts of Li-ion batteries, are being used both separately and jointly. The academic literature assessing the potential barriers of transitioning to electromobility, and its related life cycle impacts, presents a rather wide range of scenarios that differ with respect to electric vehicles deployed, and consequently Li-ion batteries and raw materials demand. However, previously analysed scenarios showed how the demand of key battery raw materials is expected to increase significantly, which in turn could require a substantial growth in the mining and further processing infrastructure, compared to current levels. Understanding the industrial capacity needs and the growth rate required across the complex value chains going from raw materials mining to Li-ion battery production can help in devising more robust decarbonization strategies across the entire value chain while avoiding bottlenecks. Technology-rich Integrated Assessment Models such as MESSAGEix can allow the assessment of the transition to electromobility under this perspective while considering potential constraints in the natural resources extraction rates, the industrial infrastructure needed to process these resources, and the emissions mitigation targets consistent with global decarbonization efforts.

This work integrates Industrial Ecology methods, i.e. MFA and LCA, and data within MESSAGEix-Materials-Transport. On the one hand, the application of MFA provides the basis for mapping the value chains of Nickel, Cobalt, Copper, Lithium and Graphite, from their mining phases until they reach the battery manufacturing facility, where they are combined into Li-ion battery technologies commonly used in electric vehicles. On the other hand, the use of emission factors calculated via LCAs provide the carbon footprints of the various processes and their inputs, allowing to analyse the emissions embodied in the raw materials and ultimately in the Li-ion batteries. The implementation of this data in an optimization model covering the nexus between energy, economy and environment allows the understanding of the conditions concerning materials availability, costs, production capacity that are required under emissions mitigation scenarios. Moreover, it is possible to analyse future upstream footprints of the raw materials coupled with a less carbon intensive energy system, which can help identifying the most sustainable sourcing strategies. With such analysis we also aim at identifying strategies where the recycling of the batteries reduces the reliance on primary raw materials extraction.

Understanding such complex interactions and their potential synergies and challenges, to inform policymakers and the relevant industrial sectors on possible strategies and pathways that ensure the deployment of Li-ion batteries and electric vehicles as sustainably as possible.

A round-trip around the world: Scenarios on circular material use in vehicles worldwide

Monday, 3rd July - 17:15: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (part 2) (C1.31 KOG)

Sebastiaan Deetman [1], ***Ester van der Voet*** [2], ***Vassilis Daioglou*** [3], ***Martijn van Engelenburg*** [4], ***Oreane Edelenbosch*** [5], ***Detlef van Vuuren*** [6]

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Part of special session: BRINGING INDUSTRIAL ECOLOGY AND THE CIRCULAR ECONOMY INTO INTEGRATED ASSESSMENT MODELS

Abstract: The coming decades will see a growing demand for worldwide transportation of both passengers and cargo. While options for lowering the greenhouse gas emissions of vehicle operation are slowly becoming visible and available, our vehicles are also becoming bigger and heavier, inevitably causing a shift in the environmental impact from the use-phase to the vehicle production stage. Largely dictated by the production of the materials used.

As part of the CIRCOMOD project, we present a scenario analysis to explore the potential reduction in the use of materials in vehicles to fulfill global transport demand towards 2060. We explore the stock-flow-service nexus of a wide variety of transport modes and vehicles, ranging from passenger cars and public transport to cargo ships, using background scenarios with global coverage from the IMAGE integrated assessment model. We explore the potential upper and lower boundaries for future use of steel, copper and aluminium in the global vehicle stock by implementing different climate-policies, resource-efficiency strategies and circular economy measures.

Results show a large fraction of the virgin raw materials required for vehicle production could be avoided by typical circular economy measures such as vehicle lightweighting, longer lifetimes and improved reuse and recycling rates. However, modal shift and reduced car ownership, i.e. demand reduction strategies, would likely have an even larger impact on material demand. Perhaps surprisingly, we also show that moving toward a circular transport sector might lead to lower rather than higher volumes of recycled materials, and we address some trade-offs between climate policies and resource efficiency strategies. Our findings emphasize the importance of linking and integrating industrial ecology tools within integrated assessment frameworks for more realistic climate policy analysis.

Adding Materials to the Climate Mitigation Picture: Material and Circular Economy Dynamics in Cost-Benefit Integrated Assessment Modeling

Monday, 3rd July - 17:30: Special Session: Bringing Industrial ecology and the Circular Economy into integrated assessment models (part 2) (C1.31 KOG)

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Increasing global population and wealth have led to a rapid rise in material consumption, causing resource depletion and waste generation, as well as high levels of energy use and related greenhouse gas (GHG) emissions from production and use of materials. The circular economy (CE) has been proposed as an alternative to the linear economic model and aims to reduce primary material consumption as well as material wastes by narrowing loops, slowing loops, and closing loops. The potential of CE and material efficiency strategies for GHG emission reductions (related to SDG 13) has been highlighted in several scientific publications, and it is believed that reducing material consumption through CE strategies could play an essential role in meeting climate targets. While cost-benefit integrated assessment models (IAMs), such as DICE, are used to assess climate policy strategies by determining cost-optimal GHG emission reduction pathways, they do not represent material stocks and flows nor the impact or potential of CE strategies for climate change mitigation pathways.

In this study, we address this gap by further developing MIMOSA, a simple and transparent cost-benefit IAM covering relevant technological and socio-economic (yet no material or CE) dynamics similar to DICE, towards a global meta-model that describes the key dynamics in which CE strategies impact climate change mitigation efforts. MIMOSA has been developed and used in existing research to examine the interaction of most significant factors, such as socio-economic developments, climate system uncertainty, damage estimates, mitigation costs and discount rates. We build on and extend the existing model by integrating a novel 'stylized' energy, material and CE modeling component. To achieve this goal, we intend to leverage the global climate and resource databases of IPCC and IRP, as well as other material/CE modeling data from existing research. Depending on data availability, we aim at decomposing the mitigation component of the existing model to include energy intensities and material intensities. Material stocks and CE measures will be represented in a global generic material model. Furthermore, these dynamics will be assessed across developed, emerging and developing world regions as well as a number of broad sectors (such as industry, transport and buildings). Implementing these dynamics in climate mitigation models will allow policymakers to build upon scenarios and insights into optimal pathways to meet Paris Agreement targets, distinguishing newly introduced CE measures from more traditional measures for climate mitigation.

Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition

Identifying research diversity of the Living Labs across different sectors

Monday, 3rd July - 16:30: Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition (B0.41 KOG)

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Living Labs are highly diverse and complex in nature. Living Labs emerged in the recent decade with the joint effort of the different stakeholders towards transition governance (Nevens et al., 2013; Schäpke et al., 2018). Living Lab innovation is not focused on single area of research, it is diverse in innovation development across various sectors. It supports development of innovation by involvement of interdisciplinary team i.e., from manufacturer to the end user with a special focus on user needs. Living Lab is a user centred research/innovation with an open and distributed approach to develop a sustainable product and/or service in a real-world environment by regular interactions with all the stakeholders involved (including users) (Evans et al., 2016; Habibipour et al., 2020; Ståhlbröst, 2012). Thus far, the publications on Living Labs are focused on defining the Living Lab (McCrory et al., 2020), its support towards innovation development (either technology (Humble, 2014; Nesti, 2018), product (Andersson & Rahe, 2017; Buhr et al., 2016) or service (Larsson & Holmberg, 2018; Zen et al., 2016)), presenting Living Lab project results (Lupp et al., 2020; Von Wirth et al., 2019), guidance on improving the user engagement (Habibipour et al., 2022; Sarjanen, 2010) etc. The present work is a review of the Living Lab diversity. This work is developed from scientific journal articles, books, reports, conference proceedings etc. published in last 15 years and available from Scopus and Web of Science. A total of 108 resources were found suitable for the present study from overall 525 resources after the abstract and case study screening. Further to this the Living Lab case studies presented in these papers are categorised based on the nature of the organisation involved in Living Lab innovation. A specific emphasis is made on the type of the research works conduced in Living Labs in different sectors. Finally, the key learning outcomes from these case studies are presented to enhance developing future Living Labs.

Making Data Analytics Less Biased: Applying the Wells-Du Bois Protocol for Achieving Systemic Equity

Monday, 3rd July - 16:45: Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition (B0.41 KOG)

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Recent decades have seen the integration of data analytics – such as machine learning (ML) - into various dimensions of modern socioecological systems, commerce, and countless sectors that leverage advanced technologies. The surfacing of sophisticated data techniques has unlocked new potential for innovation and novel research applications, but those leveraging these techniques must acknowledge the biases and flawed outcomes that can be produced when using data-centered tools and models. To address this matter, I overview relevant bias and inequity circumstances in socioecological systems. Then, I present an equity-centered framework (i.e., the Systemic Equity Framework) and tool (i.e., the Wells-Du Bois Protocol) which can be used to mitigate inequity in model outcomes of a socioecological food system. Specifically, the Wells-Du Bois Protocol was applied to a ML-clustering application, using food expenditure data from the United States Consumer Expenditure Survey, to show how equity-centered practices can help achieve systemic equity. Our findings suggest that more than simply applying ML methodology is needed when sociodemographic factors (e.g., race, ethnicity, and socioeconomic status) are embedded. Furthermore, these findings exemplify why equity-centered frameworks and tools are so important to employ in socioecological settings whether bias is apparent or not. The main takeaway is that equity-centered frameworks and tools must be systematically integrated into routine data analytic practices regardless of how benevolent the dataset and model components seem.

What are circular economies without community input? Advancing and Scaling the Circularity Assessment Protocol

Monday, 3rd July - 17:00: Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition (B0.41 KOG)

Melissa Bilec [1]***, Jenna Jambeck*** [2]***, Nicole Bell*** [1]***, Madison Werner*** [2]

1. University of Pittsburgh, 2. University of Georgia

While interest in the circular economy has increased significantly, much of the research has been on technology and products. At the same time, communities are interested in implementing circular economy strategies with each community offering unique opportunities and challenges. Integrating quantitative and qualitative, community-level data, while providing actionable circular strategies guidance, was missing. The Circularity Assessment Protocol (CAP) is a standardized assessment protocol to inform decision-makers through collecting community-level data on material usage and management; CAP was developed to address the missing community gap. CAP consists of seven spokes: input, community, material and product design, use, collection, end of cycle, and leakage. At the center, the system is driven by policy, economics, and governance with key influencers including non-governmental organizations, industry, and government. The original version of CAP, which largely focuses on plastics, has been implemented in over 30 cities and 10 countries. Currently, we are working to expand the CAP framework (Convergence CAP) to converge circularity across four different categories: molecules, plastics, organic materials, and the built environment. The Convergence CAP is being piloted in Pittsburgh, Pennsylvania, and Atlanta, Georgia in the US to connect and converge a circular pathway across multiple materials and scales. This work is bringing people together through collaborative data collection and analysis across disciplines through both researchers and the diverse stakeholders representing community members, cities, and industry. Structured interviews of non-profits, community leaders, government officials, and industry were conducted in the pilot cities, along with quantitative data to inform the Convergence CAP. Convergence CAP findings and direction will be presented. The experience from the two cities will be translated to other locations throughout the US, with the aim of scaling to cities around the world.

The Promise of Sustainable Transportation and Its Hidden Unintended Environmental Consequences

Monday, 3rd July - 17:15: Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition (B0.41 KOG)

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It is estimated that 28% of greenhouse gas emissions (GHG) in the United States come from the transportation system, with various other toxic pollutants released from carbon-intensive modes of transportation. The urgent need to reduce harmful emissions from the transportation sector has set in motion an insuppressible momentum for adopting alternative modes of transportation such as autonomous vehicles, electric vehicles, and electric bicycles. Yet the adoption of these emerging modes could overshadow potential environmental impacts that thwart efforts to create a sustainable transportation system.

Emerging modes of transportation are rapidly developing with the excitement that they can bring substantial benefits in terms of transportation sustainability. Yet, this excitement could be overshadowing potential environmental impacts. The emerging modes themselves might not lead to direct environmental impacts. However, their presence could induce significant changes in the transportation demand and supply, which cascades into environmental impacts. In this work, we aim to reveal and quantify the hidden environmental implications of different emerging modes of transportation, specifically autonomous vehicles, electric vehicles, and electric bicycles. In a series of empirical surveys performed across the U.S. cities of Madison (Wisconsin) and Chicago (Illinois), along with industry collaborations, we collect data on travelers' transportation modal choices. Data collected was used to build mathematical models on the relationships between users' preferences for different transportation modes and the cascading environmental implications. Life cycle assessment based on well to wheel model is adopted to further quantify environmental impacts across five different categories: energy consumption, greenhouse gas emissions, particulate matter, sulfur, and nitrogen oxides. Further, we analyze the dependency between the energy infrastructure, mainly the electricity generation scheme, and its impact in offsetting foreseen environmental benefits from electric modes of transportation. Finally, we design a predictive choice model to estimate the environmental rebound effect of modal transportation adoption as a function of travel characteristics.

Our analysis shows that autonomous vehicles, autonomous electric vehicles, and electric bicycles enjoy a great deal of attractiveness by travelers, which translates directly into use phase environmental impacts. Adopting autonomous vehicles will eventually increase emissions. However, autonomous electric vehicles can offset these outcomes. On the contrary, electric bicycle-sharing programs can alleviate the demand on carbon-intensive modes and reduce transportation emissions. Further, the way we generate electricity, and the dependency on unsustainable energy sources, can hinder our ability to decrease transportation emissions when adopting electric options.

This work serves as a step forward in analyzing the environmental impacts of our transportation system. Ultimately, we aim to steer the development and deployment of new modes of transportation in ways that match users' adoption needs and are environmentally beneficial.

Environmental risks and climate change adaptation and mitigation measures in a small island: The case of Rodrigues island.

Monday, 3rd July - 17:30: Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition (B0.41 KOG)

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Rodrigues island is 18.3 km long and 6.5 km wide and is situated in the south-western Indian Ocean, 600 km east of its central government in the main island of the Republic of Mauritius. Steep volcanic flanks and deep narrow valleys rise to 398 m characterizes the island with a population of 40,000 inhabitants. The island has one of the Indian Ocean's largest reef lagoons (approximately 200 m^2). The mean annual temperature for Rodrigues Island has warmed by about 1.41°C in the last 70 years (1951-2020) and the average temperature at all stations is rising at a rate of about 0.20 °C per decade. As opposed to the mainland, the day temperatures of Rodrigues Islands have warmed faster than night temperatures with an increase of 1.49°C and 1.32°C respectively. The study site (108 km^2) is largely inhabited by fisher communities and informal settlements with low-and-middle-income groups. Being autonomous, the island's actions for climate change adaptation and mitigation are closely aligned with the strategies of the main island Mauritius. Physical environment and biodiversity in Rodrigues are associated with a range of challenges and potential negative climate change impacts. There are significant pressures from agricultural activities, fisheries, as well as from urbanization and tourism, which are expected to increase with greater accessibility to these regions. Current available strategic integrated development plans date back to 2010 and currently being reviewed. This study explores the barriers for climate change adaptation and mitigation for Rodrigues Island and how application of circular economy measures can quickly transform the island and build resilience. There are very few studies conducted to guide national planners on how to adapt to climate change and less still on how to build on past adaptation experiences. The construction of institutional resilience is an important step in the process of adaptation to environmental risks. The work therefore explores the roles of persuasion, capacity development and collective key stakeholders' action in developing the ability to buffer external disturbances using the social resilience concepts. A review of the strategic plans, legislative framework, master plan for environment and study reports produced for coastal physical protection, island socio-economy resilience was conducted. Interviews were organized with the main policy and decision makers to review the adequacy of proposed mitigation and adaptation measures. From the available plans, the circularity measures proposed for the island were identified and assessed against the following criteria: generality, content validity, aggregation principle, transparency and reliability. It was observed that designing of the measure started well with an accepted definition for circular economy among key role players. However, the circular metrics were poorly defined with the consequence of inability to assess effectiveness of the circular measures proposed. Climate change mitigation measures were presented separately in environmental plans and the linkages to the circular measures not very persuasive. The study however finds that self-efficacy, strong local and international support networks, combined with a willingness to act collectively and to learn from mistakes appear to have increased the resilience of the islands' government to climate change risk. The lessons learned from building resilience to climate vulnerabilities can contribute to the creation of national level adaptive capacity to climate change and shared as success stories to other small island states with limited resources.

Understanding the Role of Value-Based Choice in Green Building and Neighbourhood Living Labs through Q-Methodology

Monday, 3rd July - 17:45: Special Session: Experiences and Impacts of User-Centric Research that can lead to much-needed Transition (B0.41 KOG)

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Current approaches to understanding end-user behaviour in buildings and neighbourhoods often rely on assumptions around habitual routines or stand-alone opinions (Chen and Gou, 2022; Heinrich *et al.*, 2022; Moeller and Bauer, 2022) . However, these approaches overlook the role of value-based choice in shaping behaviour. This paper argues that Q-methodology offers a more nuanced way of engaging with end-users and their choices in green building and neighbourhood living labs (Cuppen *et al.*, 2010; Albizua and Zografos, 2014; Damgaard, McCauley and Reid, 2022). The urgency for this research arises due to the growing number of living lab studies, as detailed in systematic reviews (Hossain, Leminen and Westerlund, 2019), that do not consider the role of choice. A systematic review (Huang and Thomas, 2021) focused on living lab research and methods for user involvement reported 41 different methods used, none of which involved value-based choice.

By applying Q-methodology, this paper proposes an innovative choice-based methodology with a focus on values of fairness and equity in building use. It builds on recent calls to expand the use of social science methods in living labs (Dekker, Rijnks and Mierau, 2021). The paper takes three real world examples which are part of large European project. The Q-methodology is proposed to understand the role of value-based choice in the building and neighbourhood use. The conclusion drawn at this early stage is that more robust co-created solutions can emerge from a better understanding of relative choice, rather than absolute opinion. Moreover, living lab methodologies need to embrace new end-user focused data collection and analysis techniques. This paper contributes to the literature on living labs methods, and specifically the thematic domain of ‘design approaches’ (Huang and Thomas, 2021), by highlighting the importance of Q-methodology in understanding end-user behaviour in green building and neighbourhood living labs. It emphasizes the need to shift towards a more nuanced understanding of end-users and their choices, which can lead to more equitable and sustainable solutions.

Built environment MFA

Development of building stock model for Thane City in India: Learnings for future stock management

Monday, 3rd July - 16:30: Built environment MFA (C0.06 KOG)

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Urbanization across the globe has resulted in major landscape changes in the built environment. Large-scale Construction and Demolition (C&D) activities are taking place to support the expansion of the cities. As developmental activities remain a vital aspect of urban growth, the high dependence of such activities on natural resources is detrimental to the overall natural systems. Therefore, the **construction sector** needs to **rethink** the approach to attain sustainability in practices without compromising on the pace of the existing growth trajectory. **Urban Mining (UM)** from building demolition waste can be one such strategy that conforms to the principles of Circular Economy and Life Cycle Thinking and can enhance the resource efficiency of the construction industry by retaining the building materials within the loop for a longer duration. Buildings are not only a large consumer of resources, but from the perspective of UM concept, they also are a storehouse for the future supply of raw materials. Developing countries like India require a robust yet sustainable construction framework to meet the future demand for materials without compromising environmental well-being. With many development projects underway, the potential of **UM** has become **highly relevant** at the national level.

In this study, **Building Material Stock Accounting** for the city called 'Thane', located in the Mumbai Metropolitan Region of India, has been carried out. The anthropogenic material stock embedded in the city up to the year 2018 has been estimated with the aim of introducing the innovative strategy of UM as a demolition waste management solution in the region. This work is the **first of its kind in the Indian context** and adopts a **novel integrated bottom-up approach** for the estimation of built-up stock by combining the spatial and building material characteristics specific to the region. Thane is an old metropolitan city that is expected to redevelop as a business hub and a location for long-term investment in the coming years, consequently, steady growth in C&D activities is expected. Geographic Information System was used to process the spatial building information such as building area, height and location. Statistical analysis using joint probability distribution was then carried out to identify the four most common building typologies in the Thane area. Each building typology thus identified was further designed, modeled and analyzed as per the Indian standard code provisions using building design software. The building material intensities at the building and building-element level in the Thane region were then derived using the results obtained from the building design. This study focused on the stock estimation of three main building elements: concrete, steel and bricks. The results showed that the total built-up stock in Thane city in the year 2018 amounts to **84.73 million metric tons (tonnes)**. **Concrete (57.7%)** is the building material that occupies the major share of stock, followed by **bricks (40.4%)** and **steel (1.9%)**. The result of this study promises high potential for the existing building material stock to be harnessed as raw materials for future construction. The **Indian construction sector** has an opportunity to become **self-reliant and regenerative** and **reduce** its environmental impact. The problems of urban sustainability are complex and diversified and the outcomes of this study can be instrumental for the decision-makers in defining new pathways of sustainable construction in India.

Material flow analysis of Great Britain's road network

Monday, 3rd July - 16:45: Built environment MFA (C0.06 KOG)

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Over the last two decades, material flow accounting/analysis or material metabolism has been increasingly applied for construction materials to estimate past and current material stocks and flows and predict future stock development. This development is partly driven by the circular economy approach, adopted into legislation and company policies. In addition, the commitment to reduce greenhouse gas emissions to net zero requires tools to determine and track embodied emissions. Hence, increasing knowledge of the materials circulating and accumulating in the anthroposphere is required. Previous studies on construction materials mainly employed bottom-up approaches to determine the material stocks of cities, regions, or countries. These studies revealed that construction materials significantly contribute to the global material flows and stocks, representing nearly 50% of the global materials used. The transportation infrastructures, primarily road networks, represent the second largest stock within the construction stock. In addition, road structures act as a recipient of cascading materials, increasing recycling rates.

The material flow analysis of Great Britain's road network showed that mineral aggregates are the main materials used in road construction and roads consume about 20% of the primary mineral aggregates supplied. The dominance of mineral aggregates is due to their use in the production of asphalt and cement and in the construction of unbound road layers. On average, 87% of aggregates used in asphalt production were crushed rocks. As most paved roads in Great Britain have an asphalt surface, the annual asphalt flow into the road network was of similar quantity as uncoated stones in unbound layers flow. The higher share of asphalt indicates that road network maintenance increasingly uses more materials than new road constructions. This relation is further reflected in the high share of produced asphalt for surface wearing courses. A slight increase in reclaimed asphalt was observed over the past decade. The amount of reclaimed asphalt could potentially substitute 19wt% ±0.04wt% of the annual asphalt production. However, reclaimed asphalt accounts for 10wt% ±3wt% of the annual asphalt production. The rest is used mainly in unbound road layers or backfilling. Downcycling is practiced due to low material quality, economical transport distance, less economically feasible compared to primary materials, lack of storage facilities, and a practised conservative attitude of road authorities regarding the application of innovative materials due to safety and cost concerns.

An often neglected flow is the dissipative material flow. The dissipative flow for roads originates from the surface interaction of tires and pavement, causing abrasion, ravelling, and potholes. Great Britain's road authorities annually fill about 1.9 million potholes. The estimated required material to fill these potholes is about 0.34 Mt per year. Since pothole repair requires a certain depth and area (ensuring material bonding), it was assumed that the responding pothole induced dissipative material flow is about 10% to 20% higher. The resulting annual dissipative flow, including abrasion, accounts for 0.39 Mt ±0.02 Mt (~2% of the annual asphalt production), which needs to be replaced with primary or cascading materials and will gain more significance in an established circular economy.

A future challenge to road material flow analysis is the optimisation of flows and stocks to sustainably reduce primary material consumption, internally recycle materials from and into stocks with different dwell times (affected by climate change and increased traffic), and determine lasting temporal sinks in the anthroposphere to reduce deposition in landfills.

A material flow analysis of sand use in the Netherlands

Monday, 3rd July - 17:00: Built environment MFA (C0.06 KOG)

Catrin Böcher [1]***, Tomer Fishman*** [2]***, José Mogollón*** [1]***, Ester van der Voet*** [3]

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While often considered abundant, sand is currently being used at an unsustainable rate as the amount of sand used exceeds natural replenishment rates. Furthermore, sand mining can have serious environmental consequences. Considering the globally increasing rate of construction, land reclamation and coastal protection projects, together with other industrial uses of sand, global demand for sand will only increase in coming decades. Research on sand from a sustainability perspective has only started to emerge in recent years. In this research, we look at the stocks and flows of sand in the Netherlands. The Netherlands is an interesting case study, as it is a country that will be at high risk by rising sea levels resulting in a great need for coastal protection. This risk exposure is likely to considerably increase the demand for sand in the Netherlands. Furthermore, the Netherlands, together with Belgium, is an important player in the global sand dredging industry. Using material flow analysis (MFA), we quantify the current stocks and flows of sand in the Netherlands. This will help to get a better understanding of the types and quantities of sand used and understand some dynamics around it. This research will help to identify inefficiencies and losses in how we use sand. These insights will contribute to a better understanding of how we can manage our sand resources in more sustainable ways.

Spatially-refined stock-flow modeling to reveal locational impacts of envelope improvements and climate change on China's housing energy use

Monday, 3rd July - 17:15: Built environment MFA (C0.06 KOG)

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The global building sector accounts for ~30% of the final energy consumption. Given its importance in both climate change mitigation and adaptation, there have been many increased calls for improving building efficiencies across many countries. Primary among these is the rapid deployment of efficient building retrofits (improving building envelopes). While there will be some improvement in energy efficiency via renovating existing buildings and replacing older buildings with more energy-efficient new buildings, it remains unclear to what extent these measures could improve energy efficiency in buildings. More importantly, recent evidence shows that building energy use is subject not only to building stock characteristics but also to climate change. Climate change is strongly location-dependent, and so are its impacts on building energy use.

Here, we diagnose the compound effects of envelope improvements and climate change on China's housing energy use by a building physics-based model with fine spatial and temporal granularity. We identify patterns of housing energy use under three climate change scenarios (i.e., SSP1-2.6, SSP2-4.5, and SSP5-8.5). In addition to these climate scenarios, we develop three pathways that reflect various levels of improvements in building envelopes (i.e., Reference, Moderate, and Radical). These three climate scenarios and three envelope scenarios result in nine scenarios (3×3) for assessing overall interactions between building envelope improvements and climate change.

We apply our model to building stock data for 1,677 sub-province-level cities in China, where each city is represented by multiple building vintages. Using a machine-learning-enabled surrogate model to expedite a computationally expensive building energy simulation, we model the impacts of temperature changes on the cooling and heating demands of China's residential building stock. We find that envelope improvements play a varying role in ameliorating the impacts of changing climate on housing energy use, highlighting the need for building climate-resilient energy supply and pursuing alternative energy efficiency strategies in less climate-resilient regions.

Building Decarbonisation at Scale: Dynamic Stock-Flow Modelling of Pathways Across Germany’s 10,000+ Municipalities

Monday, 3rd July - 17:30: Built environment MFA (C0.06 KOG)

Jakob Napiontek [1], Tomer Fishman [2], Peter-Paul Pichler [1], Helga Weisz [1]

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In the Paris Climate Agreement of 2015, the signatory countries agreed on binding reduction targets for greenhouse gas emissions. Germany has also formulated climate targets, although the concrete path to achieving them is still rather vague, especially in the building sector. Researchers have made great strides in applying complex dynamic stock-flow models to generate realistic scenarios of building stock trajectories and associated emissions. Scenarios from previous studies of Germany’s future building stock have so far not met Germany’s emissions targets.

This research project advances these studies by developing such target scenarios within the Resource Efficiency-Climate Change (RECC) modelling framework. The RECC framework links services (e.g. shelter) with the operation of product stocks in use (e.g. buildings), their material cycles and their respective emissions. The target scenarios, built using the RECC Germany database, explore the conditions necessary to meet the German government’s targets for the building sector by 2030 and 2045. They describe the extent of material efficiency strategies such as floor space reduction and cover all major building materials (aluminium, cement, concrete aggregates, copper, plastics, steel, wood and zinc). These scenarios are valuable tools for describing the necessary transitions in Germany’s industrial metabolism.
However, the fact that their results are aggregated at the national level hinders the development of specific regionalised policies, which is particularly important in Germany’s federalised housing policy. To address this shortcoming, this project adds geographical and socio-economic resolution to the material flow analysis using synthetic population microdata from Germany. This makes it possible to assess the emissions of the building system at the level of more than 10000 municipalities across Germany and for individual socio-economic groups, e.g. based on income, education level or home ownership.

Unsaturated and Accelerating Material Stock Accumulation in China’s Megacities as Urbanization Approaches 80%

Monday, 3rd July - 17:45: Built environment MFA (C0.06 KOG)

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The accumulation of material stock serves as the foundation for human production and daily life. This stock is utilized by families, governments, public entities, and industrial sectors to support activities such as living, working, transportation, and communication. The evolution of the socioeconomic system affects the demand for material stock, leading to changes in its consumption and driving the overall social metabolism. Despite its significance, the impact of urban material stock accumulation remains unclear. By examining the relationship between socioeconomic development and material stock accumulation, as well as its environmental impact, we can optimize resource demand and allocation in urban areas, thereby improving efficiency and reducing the burden on global resources and the environment.

Megacities, with their long lifespan and high throughput, serve as ideal subjects for studying urban metabolism. This study analyzed 111 types of in-use stocks in 8 megacities in China, exploring their relationship with socioeconomic development and environmental impact. The in-use stocks in these cities rapidly accumulated from a mere 350 million tons in 1978 to the gigaton level in 2018, with increases ranging from 6 to 248 times. The growth of China’s megacity GDPs has reduced dependence on stock accumulation, the stock productivity has been increasing over the past 40 years (with an average increase of 7 times). The improvement in stock productivity and resource utilization efficiency has reduced CO_2 emissions by 154-505 million tons and saved 11-594 million tce of energy and 132-380 million tons of food. Despite this progress, population growth and deepening urbanization continue to drive stock accumulation. When the urbanization rate reaches approximately 80%, the relationship between per capita material stock and urbanization rate enters a “highly sensitive period,” with every 1% increase in urbanization resulting in an average increase of 13.5, 1.9, and 0.6 tons of per capita buildings, infrastructure, and durable goods, respectively. The results of this study provide a basis for effective resource circulation and stock management and offer insights into the future development of other cities.

LCA and circularity

Improved land management by growing wheat in rotation with lupine and fallow

Monday, 3rd July - 16:30: LCA and circularity (B0.25 KOG)

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Agriculture is the main driver of land degradation and biodiversity loss and is responsible for almost one-third of global greenhouse gas emissions (The World Bank, 2021). In this sense, UNEP reported that 86% of species under extinction risk are threatened by agriculture (Benton et al., 2021). In addition, it is estimated that intensive agriculture practices generate 10 million hectares of unproductive cropland every year (Hossain et al., 2020). Crop rotation is recognized as a more sustainable strategy, which brings numerous ecosystem services (e.g., N-fixation, pest regulation, increments of yields) and supports a more efficient use of resources (EIP-AGRI, 2020; Köpke and Nemecek, 2010; Rebolledo-Leiva et al., 2022; Rose et al., 2023). Wheat is a basic commodity, accounting for 20% of global food calories (Poole et al., 2021). In Galicia (NW Spain), the recent Protected Geographical Indication (PGI) “Pan Gallego” has underlined the importance of wheat quality in the production of Galician bread, thus encouraging the cultivation of local wheat varieties (Almeida-García et al., 2022). The present study analyzes the environmental performance of a three-year rotation consisting of a native Galician variety of wheat (eco-type Carral), lupine and a fallow period. The attributional Life Cycle Assessment (LCA) methodology has been applied to three agricultural scenarios: A (fallow-lupine-wheat), B (lupine-fallow-wheat) and C (wheat-wheat-wheat). Primary data was collected directly from farmers and it was complemented with the Ecoinvent database (Wernet et al., 2016) for the background processes. The land management functional unit (one hectare·year) was considered, aiming to identify, from an environmental point of view, the best use of land to grow local wheat. Ultimately, a more environmentally friendly wheat production will contribute to increasing the added value of Galician bread. LCA impacts were evaluated according to four impact categories: Global Warming (GW), Freshwater Eutrophication (FE), Soil Organic Carbon Deficit Potential (SOC) and global Potential Species Loss (PDF). The results indicate that the monoculture system (C) is the worst scenario, while A has the best environmental performance across all impact categories. The most remarkable improvement is found in GW, where the rotation systems outperform the monoculture with a reduction of 119% and 56% (A and B respectively). In the case of A, its negative GW profile (-114.31 kg $CO_2eq \cdot ha^{-1} \cdot year^{-1}$) is linked to the soil carbon capture by returning straw to the field, representing a carbon credit. Regarding PDF, its impact is mainly attributed to land conversion, while SOC is influenced by land occupation pressures. Given that the three agricultural systems studied are developed in the same ecoregion (PA0406 Cantabrian mixed forests) (Olson et al., 2001), with the same species density, threat level and proportion of natural habitat lost, all scenarios share a similar PDF impact. In the future, it would be valuable to evaluate these systems from a production and economic perspective to ensure that environmental improvements are accompanied by a benefit to farmers.

Acknowledgments

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Closing the NPK Cycle in Urban Areas. The Use of OMSW Compost for Peri-urban and Urban Agriculture.

Monday, 3rd July - 16:45: LCA and circularity (B0.25 KOG)

Juan David Arosemena [1]***, Susana Toboso*** [1]***, gara villalba*** [2]

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Cities need to address food supply and management of organic municipal solid waste (OMSW) amid urban growth. Urban agriculture (UA) has the potential of addressing these issues, by providing local crops fertilized by recovered nutrients from OMSW compost. This research aims to determine the capacity and environmental impacts of supplying nitrogen, phosphorus, and potassium (NPK) from composting OMSW to meet UA nutrient demand, considering the environmental benefits of replacing mineral fertilizer while minimizing waste using life cycle assessment (LCA). The Metropolitan Area of Barcelona (AMB) serves as the area of study, for which official agricultural spatial data and reports from different types of centralized OMSW facilities were analyzed to determine the nutrient demand and the compost supply potential, respectively. The results concluded that the current annual production of 68, 800 tonnes of fresh produce of the AMB requires a yearly total of 769 tonnes of N, 158 tonnes of P, and 592 tonnes of K, currently supplied mostly by mineral fertilizers. Our study indicates that compost from OMSW can potentially supply 7% of the total demand of NPK, given current infrastructures, capacity, and waste collection practices, and up to 21% if the compost production system is increased according to the AMB's waste management program goals. An LCA was performed to determine the impacts associated to supplying the total yearly NPK demand with mineral fertilizer only and by combining mineral with different compost production scenarios (current and future). Results indicate that a mineral fertilizer scenario has more impacts than when combining it with compost, with significant differences in Mineral Resource Scarcity (33%), Marine Eutrophication (46%), and Fossil Resource Scarcity (78%), when compared to the scenario where 21% of the nutrient need is met by compost. The avoided burdens associated with preventing landfilling and energy recovery from biogas resulted in environmental savings equal to 9% of the total net carbon footprint (Global Warming) of the MSW system in the AMB and 17 times less in Freshwater Eutrophication than what was generated in the mineral fertilizer only scenario, even when including the impacts associated to the compost production in the anaerobic digestion facilities. This study aims to inform policy makers about the benefits of circularity of nutrients by considering their entire life cycle in the city, from waste to crop, to systemically quantify the benefits beyond the waste management facilities and beyond urban agriculture.

Life Cycle Assessment and Techno-Economic Analysis of Waste-Based Enhanced Weathering in the United States

Monday, 3rd July - 17:00: LCA and circularity (B0.25 KOG)

Jennifer Kroeger [1], ***Bingquan Zhang*** [1], ***Noah Planavsky*** [2], ***Yuan Yao*** [1]

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Enhanced rock weathering (ERW) is a proposed strategy for removing carbon from the atmosphere to mitigate climate change. The IPCC's AR6 report and recent U.S. government initiatives identify ERW as a promising carbon dioxide removal (CDR) approach for meeting international and national net-zero goals. While national and global ERW CDR potentials have been analyzed in existing literature, regional ERW potential and economic feasibility in the U.S. have not been fully explored or quantified. The real-world supply chain constraints have also been rarely considered in previous ERW studies. Additionally, industrial and construction waste materials with silicate properties have been proposed as a potential wide-spread source for ERW material to integrate circular economy principles and CDR. However, waste impact on ERW costs and net CDR has not been fully quantified. As the U.S. continues to develop CDR goals, it is critical to understand the cost, CDR potential, and supply chain constraints of ERW sourcing and applications in the U.S..

We address these research gaps using a combined life cycle assessment (LCA) and techno-economic analysis (TEA) for ERW implementation in the Midwest U.S.. Specifically, we explore the use of mining waste applied to regional agricultural lands to identify the economic and environmental benefits of employing a circular ERW supply chain. LCA and TEA are interlinked within an optimization framework to assess how varied transportation distances and approaches impact CDR potential and cost. This framework also identifies transportation pathways for a range of CDR cost targets. Real-world constraints on transportation infrastructure and agricultural lands are considered through geospatial analysis.

We find that the CDR cost of ERW in the Midwestern U.S. is between US$45 and 472 per tonne (t) of net CO_2 captured, which is competitive with other CDR technologies such as direct air carbon capture and storage and bioenergy with carbon capture and storage, and comparable to biochar production and soil carbon sequestration. Our LCA estimates cradle-to-farm gate GHG emissions of ERW in the Midwestern U.S. between 41 and 360 kg CO_2e/tonne CO_2e captured. Our sensitivity analysis identifies CDR yields and transportation pathways as the driving factors of CDR potential and cost of ERW. Furthermore, our talk will discuss the flexibility of the integrated framework for ERW applications in other regions or projects utilizing different source materials. This presentation will highlight important economic and environmental considerations for establishing ERW supply chains and application plans in the U.S., and how to effectively synergize circular economy and ERW strategies.

Environmental Consequences of Shifting Hardwood Utilization from Energy Use to Material Application - A Regional Case Study in Germany

Monday, 3rd July - 17:15: LCA and circularity (B0.25 KOG)

Anna Sander-Titgemeyer [1], *Gabriele Weber-Blaschke* [1]

1. Technical University of Munich

Forests with a high percentage of softwood tree species are affected more and more from increasing environmental stress events in Germany, such as heatwaves, droughts and insect diseases. For around 40 years, the percentages of hardwood tree species are being increased to adapt the forests to the conditions of climate change. However, at present, 90 % of the wood products in material applications are made from softwoods in Germany, while two thirds of the harvested hardwood is burned for energy production. A shift from the low value energy use of hardwood to material application is under consideration in research and practice to react to the decreasing softwood availability and to increase the value of hardwood utilization.

So far, German regulations have fostered the use of wood for energy production so that the market competition is currently biased. The recent event of the Russian war against Ukraine and following sanctions by the European Union against Russia, has led to diminished imports of natural gas and oil for heat production, which has created a new demand for the continuous use of wood in energy production. These market drivers affect the current and future hardwood utilization and thus, it is necessary to add the ecological perspective for political decision-making.

The question of hardwood utilization from an environmental perspective is addressed by assessing the shift from energy use to material application by using regional scenarios for the federal state, Bavaria, in Germany. Bavaria is chosen because it is the federal state in Germany with the biggest forest areas. The combined implementation of emerging hardwood-based products is assessed using consequential life cycle assessment (CLCA) to compare pre-defined scenarios, e.g. textile production from hardwood-based cellulose. System information from the simulation of the future hardwood availability and the material flows in the current hardwood value chain of Bavaria serve as inputs for the development of hardwood utilization scenarios. The modeling of the scenarios include system expansion to account for the manifold by-products inherent to wood processing. The affected production processes for the by-products are identified by using the 5-step-approach by Weidema [1].

Additionally, the product market of (hard)wood is diversifying. New paths and products in the field of chemistry and biology are being developed and gaining importance. Three emerging hardwood products have been assessed on a prospective attributional level. The different production-paths of the emerging products will be included in the scenarios. The affected incumbent technologies substituted by the hardwood products were identified based on expert information and checked with the 5-step-approach. When including emerging products, future system changes need to be considered when applying CLCA, which means including changes in the (consequential) background data base. In the end, recommendations for the utilization of hardwood are derived including the transferability to other regions in Europe.

[1] The approach is described in Weidema, B.; Frees, N.; Nielsen, A.-M.(1999): Marginal Production Technologies for Life Cycle Inventories. In Int J Life Cycle Assess 4 (1), pp. 48–56.

Evaluation methodology of recycled content for metals

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 17:30: LCA and circularity (B0.25 KOG)

Taichi Suzuki [1] ***, Ichiro Daigo*** [2]

1. The University of Tokyo, UACJ Corporation, 2. The University of Tokyo

Recycled content (RC) is one of the well-known indices of recycling, representing the ratio of recycled metals used for a new product. It is used for an environmental claim of a product to highlight recycling awareness. The evaluation method of RC for a product is defined in ISO 14021 as “the proportion, by mass, of recycled material in a product or packaging,” and many products follow this definition. Based on ISO 14021, the RC of a product composed of metals can be calculated as the weighted average of the content of recycled metals used in the target product. It would be easy to calculate the RC if the metals were explicitly regarded as recycled or non-recycled metals. Therefore, to determine the RC of a product, the RC of a specific metal composing a product must be evaluated. The RC of metals is defined in the report by UNEP as “the fraction of secondary (scrap) metal in the total metal input of metal production.” The UNEP definition can be smoothly applied for evaluating the average of the RC of metals among all the applications in the system. However, the definition cannot be smoothly applied to the RC of a specific metal. When fabricating a specific metal, there is an input of scrap directly returned from a manufacturer to a fabricator, in addition to scrap purchased from the market. The UNEP definition cannot sufficiently differentiate such return and the scrap from the market. It may result in unfair evaluations, even overestimation, if such return is regarded as secondary raw material (SRM). To apply this definition for a specific metal, one should supplementally define the target process of the evaluation and inputs to the process.

RC of a specific metal shall represent the ratio of substance derived from secondary resources contained. Empirically, RC of a specific metal shall be quantified by using the information on the inputs to the fabrication process in which the chemical composition is determined. It is because the ratio of input of raw materials determines both chemical composition and RC. Once the chemical composition is determined, basically, it will not change in the following fabrication processes. We proposed the additional definition of SRMs as “input materials which are recovered by the waste management, and otherwise, they would have been disposed of.” Empirically, we defined a practice to refer to the origin of new scrap so that it can be clarified how much SRM is contained in the new scrap. Based on the definitions and practice above, we developed the calculation formula for RC for a specific metal. It follows two levels required for a specific metal; representative RC in a company or a factory level and individual RC in a specific batch level.

By applying our supplemental definitions and practice, the RC of a specific metal can be evaluated. An overestimation of RC can be avoided by referring to the origin of new scrap, though the conventional definition cannot. The proposed practice can evaluate comparable RC regardless of the system boundary set for the evaluation. To improve the RC, a fabricator is required to utilize traceable new scrap, as the new scrap without details of origin cannot be regarded as SRM. Thus, fair, comparable, and traceable RC for a specific metal can be obtained.

Current and future key factors for the environmental performance of plastic packaging waste management

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Monday, 3rd July - 17:45: LCA and circularity (B0.25 KOG)

Sarah Schmidt [1], ***David Laner*** [1]

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For mitigating the climate crisis, an extensive transformation of material and energy systems is needed. This transformation is likely to affect various sectors directly or indirectly. Among others, the environmental performance of plastic packaging waste management is expected to be affected, for example by decreasing credits for the provision of recycled materials or recovered energy. Although plastic packaging is often criticized as a symbol for the so called make-use-dispose economy, plastic is expected to remain a popular packaging material because of its low weight, low costs, good processability, and customizable features. Therefore, the development and optimization of sustainable plastic packaging waste management strategies remains a critical task also with respect to the ongoing transition of material and energy systems towards higher levels of circularity. The aim of our research was to assess the current and potential future performance of plastic packaging waste management in Germany in view of an extensive transformation of material and energy systems in terms of environmental impacts, health impacts and resource depletion issues and to identify key factors for future optimization.

The current environmental performance of plastic packaging waste management in Germany was evaluated by performing life cycle assessment (LCA). To account for anticipated extensive transformations of material and energy systems, the background system of the LCA model was adapted to prospective changes based on the output results of the integrated assessment models IMAGE and REMIND under consideration of a limitation of global warming to 1.5 °C. Based on the adapted life cycle inventories, LCA scores and sensitivity ratios were calculated for the years 2025, 2030, 2040, 2045 and 2050 to identify potential trends regarding the future development of the environmental performance of plastic packaging waste management and its key factors. Key factors for the environmental performance were identified by means of perturbation analysis. It was shown that plastic packaging waste management in Germany is associated with environmental benefits in all considered impact categories and time steps. Although net environmental benefits of plastic packaging waste management persist over time, the anticipated transformation of material and energy systems results in a decrease of the observed benefits. The results of the prospective LCA highlight that potential measures for improving the environmental performance of plastic packaging waste management should focus on the identified key factors, such as separating plastic packaging waste from the residual waste (in households or in waste treatment facilities) as well as increasing the quantities and qualities of recycled plastics. The present study highlights the utility of fine-grained analysis of environmental performance mechanisms for waste management systems in view of changing boundary conditions using the example of plastic waste management. In the future, further case studies are needed to enable sound decision support on strategies for environmentally robust waste management in view of dramatic anticipated changes in material and energy systems.

Footprints 2

Food nitrogen footprint of states and union territories in India

Monday, 3rd July - 16:30: Footprints 2 (B0.31 KOG)

***Aurup Ratan Dhar** [1], **Azusa Oita** [2], **Himadri Kaushik** [3], **Ananta Narayan Panda** [3], **Tapan Kumar Adhya** [3], **Kazuyo Matsubae** [4]*

1. Graduate School of Environmental Studies, Tohoku University, and Research Institute for Humanity and Nature, 2. Institute for Agro-Environmental Sciences, National Agriculture and Food Research Organization, 3. School of Biotechnology, Kalinga Institute of Industrial Technology (Deemed University), 4. Graduate School of Environmental Studies, Tohoku University

Background

Nitrogen (N) is a primary macronutrient for all living organisms, loss of which in the environment induced by the agro-food system is known to result in both environmental and health problems. The N footprint quantifies reactive nitrogen (Nr, nitrogen compounds other than N_2 gas) loss to the environment due to anthropogenic activities[1]. Food consumption patterns subject to religious edicts largely influence the food N footprint[2]. India, composed of 28 states and 7 union territories, has diverse religious followings[3]. Correlations between religion and diet can be simply expressed in terms of either vegetarianism (not consuming animal-based foods) or non-vegetarianism (no restriction to the consumption of animal-based foods). This study quantifies Indian state and union territory-specific food N footprint associated with food consumption taboos of two diet groups, vegetarians and non-vegetarians. The findings of this study is anticipated to support policymakers to implement efficient and effective N management policies at the sub-national level of India.

Methods

A diet-sensitive N-calculator method was used to estimate the food N footprint, which is similar to the religion-sensitive N-calculator developed by Dhar et al. (2022). Vegetarian and non-vegetarian dietary regulations were considered. Data for food supply and consumption at state and union territory levels were provided by the Ministry of Program Implementation and Statistics and the Ministry of Agriculture and Farmers Welfare for 2011–2012.

Results and Discussion

The study reveals that the total N in the consumed food was 4115 Gg-N year^{-1}. The highest amounts of N in consumed food were estimated for Uttar Pradesh (19.83 Gg-N year^{-1}) and the lowest one was estimated for Lakshadweep (0.01 Gg-N year^{-1}), the largest and smallest territory of India, respectively. The average nitrogen use efficiency (NUE) of crop cultivation was found as 19%. The NUE was found to be highest (41%) in Delhi and lowest (close to 0%) in Daman and Diu, the northern and western region of India, respectively. The average personal food N footprint was estimated at 13.11 kg-N capita^{-1} year^{-1}. The personal food N footprints of non-vegetarians were considerably higher than those of vegetarians in all territories examined. The highest per-capita food N footprint was 18.88 kg-N capita^{-1} year^{-1} for Sikkim, wherein that of vegetarians was 18.16 kg-N capita^{-1} year^{-1} and that of nonvegetarians was 18.98 kg-N capita^{-1} year^{-1}. The lowest per-capita food N footprint was 6.86 kg-N capita^{-1} year^{-1} for Chandigarh, wherein that of vegetarians and non-vegetarians was 6.32 kg-N capita^{-1} year^{-1} and 7.96 kg-N capita^{-1} year^{-1}, respectively. Cereals, the staple food in India, were found to provide the highest contributions to the food N footprint of India, followed by 'milk and dairy products', whereas 'fish and seafood' and eggs provided the lowest contributions.

Conclusion

This study concludes that while the choice of plant-based or animal-based foods is personal, a preference of plant-based food by a population can lower food N footprint at sub-national and national levels. The study recommends formulating policy options for improving crop cultivation NUE at the production-level, and choosing a diet dominated by plant-based foods for minimizing the food N footprint of India.

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THE EVOLUTION OF NITROGEN FOOTPRINT EMBEDDED IN THE GLOBAL FOOD SUPPLY CHAIN FROM 1986-2020

Monday, 3rd July - 16:45: Footprints 2 (B0.31 KOG)

Yue Xiao [1], ***Martin Bruckner*** [2], ***Stefan Trsek*** [1], ***Quanliang Ye*** [3], ***Anna Muntwyler*** [2]

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Reactive nitrogen emissions to the atmosphere and water bodies harm human health and the ecological system. Thus, researchers have addressed nitrogen pollution more intensely during the past decades from both production and consumption perspectives[1]. Models are a powerful instrument to investigate nitrogen emissions. Examples of nitrogen pollution assessment models include the NUFER model[2], N-calculator[3] and NutrIO[4].

Anthropogenic reactive nitrogen emissions are largely caused by agricultural production and food consumption. However, little knowledge exists on the nitrogen flows along the global agri-food supply chain at higher commodity detail and over a long-time span. The main reasons are lack of long-term relevant data and difficulties in harmonizing datasets with different classifications. With the advantages of the Food and Biomass Input-Output (FABIO) [5] model in high commodity details and compatibility with FAOSTAT datasets, this paper fills this gap by estimating and analysing the dynamics of the nitrogen emissions embedded in the global supply chain for 123 agri-food commodities from 1986 to 2020.

We conducted a multiregional input-output (MRIO) analysis based on the nitrogen-extended (FABIO) model to derive the nitrogen footprint embedded in the food supply chain. For this, we used the IPCC N cycle model and FAOSTAT crop nutrient budget data to quantify nitrogen emissions in the form of nitrogen dioxide (NO_2), nitrogen oxides (NO_x), ammonia (NH_3), and nitrogen exportable to water (N_{wp}) from agricultural production.

The results show that the total nitrogen emissions (at N equivalent) embedded in the global food supply chain doubled from 24.22 Mt N yr^{-1} in 1986 to 45.13 Mt N yr^{-1} in 2020. China, the USA and India were the top three emitting countries throughout these 35 years. In the meantime, the world per-capita nitrogen emission footprint grew from 4.9 to 5.8 kg cap^{-1} yr^{-1}, with the largest increase occurring in the Middle Eastern countries, where more than 90% of emission footprints were located overseas. For instance, the United Arab Emirates caused the highest per capita nitrogen footprint (99.05 kg cap^{-1} yr^{-1}) in 2020, with 99% of the demand-driven nitrogen pollution emitted abroad. The major N form emitted is Nwp, which accounts for 69% of total nitrogen emissions, followed by NH_3 and NO_x (27%) and NO_2 (2%) for all years.

In summary, the three largest and most populous countries (China, the USA and India) account for more than 40% of the total nitrogen footprint embedded in the global food supply chain, with domestic nitrogen emissions dominating and foreign nitrogen emissions increasing slightly over the 35 years. We conclude that the globalization of previously localized food production, a shift in consumer preferences towards animal-based foods and deepened participation of emerging economies in global trade over the 35 years have resulted in more nitrogen pollution emitted abroad. However, the main nitrogen exchange path is between developed and developing countries.

The main results are consistent with other studies[6,7], with some incoherences stemming from differences in the system boundary. With a better understanding of the N cycle and increased availability of observational data from field studies, future MRIO analysis can consider heterogeneity in regional agro-ecological systems[8]. Further inclusion of embodied energy in the global food supply chain in addition to water[9], land[10] and nutrient footprints would also be beneficiary for integrated policy design and global cooperation in addressing food security and ecological challenges.

Material-carbon nexus of urban systems

Monday, 3rd July - 17:00: Footprints 2 (B0.31 KOG)

Juudit Ottelin [1], ***Julia Sborz*** [1]

1. *NTNU*

Efforts have been made on reducing carbon footprints to achieve environmental sustainability. These often come as clean technologies that focus on reducing carbon emissions, but many of them depend on specific resources such as metal ores. Therefore, a broad subject like environmental sustainability calls for a more comprehensive analysis that also accounts for resource use. We propose to investigate the material-carbon nexus at different levels of urbanization. Our work aims to reveal the potential co-benefits and trade-offs between carbon and material footprints in urban systems. This will be achieved using a combination of a global multi-regional-input-output model, Exiobase, to the results from Eurostat's Household Budget Survey 2015 to estimate the material footprints of lifestyles in different urban degrees. Material footprints were estimated for 2603 households in Finland. Previous research on carbon footprints has used similar methods, revealing rebound effects in lifestyles thought of as sustainable. Combining this method within a nexus study will verify the impacts of carbon footprint reduction in material footprint and vice-versa. The expenditure data enables the comparison of households with similar expenditure totals that are distributed in different manners. Information on the level of urbanization of the household is also available. This methodology allows us to compare different lifestyles that cost the same to understand key sustainable behaviors and how they are linked to the urban environment. Comparisons are to be made in terms of transportation means and utility usage, which can be related to the energy transition and infrastructure. Preliminary results show that the material footprint increases with urbanization. The difference in material footprint from suburban to urban areas is higher than the difference from rural to suburban areas for all income ranges.

Green technological developments, sustainable consumption, and relocation strategies: relative effectiveness to reduce the carbon footprint of France by 2050

Monday, 3rd July - 17:15: Footprints 2 (B0.31 KOG)

Bruno Fontaine [1], ***Fanny Vicard*** [2], ***Antoine Teixeira*** [3], ***Julien Lefèvre*** [4]

1. *CIRED,* ***2.*** *ADEME,* ***3.*** *ADEME / CIRED,* ***4.*** *AgroParisTech / CIRED*

To reach the 1.5°C target set by the Paris Agreement, most of the world's countries have committed to achieve carbon neutrality by mid-century (see https://zerotracker.net/). It translates into the development of national and sectorial roadmaps to cancel direct territorial emissions in energy supply, agriculture, buildings, transport, and industry. But additionally, GHG emissions embodied in trade account for a major contribution of the carbon footprint of western countries. It originates to a large extend from the production of materials in developing countries, whose decarbonization potential is still uncertain. Secondly, the significant investments required for the energy transition and the associated macroeconomic evolutions on structural change, importations and final consumption levels can affect GHG emissions and footprint.

The design of stringent climate policies needs a clearer vision of the relative effectiveness of every possible strategies to reduce the carbon footprint of western countries and ensure the 1.5°C target. The academic literature identifies a large range of options to translate mitigation objectives at national scale: (i) Green technological developments allowing for energy efficiency gains in production processes; (ii) Improving production processes towards greater material efficiency and circular economy; (iii) Shifting the source of domestic demand to support imports of clean industrial products, and even relocating industrial production; (iv) Prioritizing consumption needs toward a more sober society. In fact, from a national policy perspective, GHG emissions reduction options can be resumed as follows : sobriety levers (changing lifestyles and reducing final consumption levels to help lowering its environmental footprints) vs efficiency levers (reducing impacts of economic activities through technology improvements while keeping consumption levels constants). Here, we discuss the relative effectiveness of each mitigation options listed above to abate the carbon footprint of western countries.

Based on the prospective exercise "Transition(s) 2050" performed by the French environmental agency (ADEME), we build two contrasted scenarios: (i) "Green Growth" (GG) scenario relying mostly on decarbonization technologies rather than reduced consumption; (ii) "Regional Cooperation" (RC) assuming changes in lifestyles toward more sustainable consumption and local production patterns. We compare both scenarios to a trend scenario in 2050. Based on the Hybrid Input-Output (HIO) model MatMat we developed, we assess and map the carbon and materials footprint of both scenarios. We found out that both scenarios enable to decrease the carbon and materials footprints by 2050. The RC scenario based on lifestyles change and relocation strategies is more efficient to reduce both environmental footprints. While the GG scenario reduce the material footprint by -14% and the carbon footprint by -30% compared to the trend scenario, the RC scenario decreases them respectively by -24% and -39%. By breaking down both scenarios into smaller coherent projection packages, we propose a detailed analysis of the relative effectiveness of each mitigation options previously listed to abate the carbon footprint of France.

Uncovering the household carbon footprint of people certified for long-term care in Japan

Monday, 3rd July - 17:30: Footprints 2 (B0.31 KOG)

Narumi Kira [1]***, Yosuke Shigetomi*** [1]
1. Nagasaki University

As Japan's population ages, the number of people who are certified for long-term care is also increasing, which is predicted by 9.77 million people in 2045. Such progress in an aging society and the increase in those people will affect the structure of household consumption. In this sense, Nansai et al. (2020) clarified that the consumption-based greenhouse gas (GHG) emissions (i.e. carbon footprint; CF) derived from nursing care services accounted for 10.1 Mt-CO_2eq in 2011. However, it is unclear how much the people who need long-term care contribute to these emissions yet. Shigetomi et al. (2014) estimated that the Japanese household CF will decrease by 4.2 % from 2005 to 2035 as a lower birth rate with an aging population. However, this estimation assumed that the consumption pattern of each bracket of the age of household head in 2005 would be fixed until 2035, not taking account into the change in consumption patterns. Against this backdrop, we aim at highlighting both the CF of households with people who are certified for long-term care and the impact of the increase in those people on future CF.

To achieve this objective, an environmental input-output analysis combined with the domestic household consumption data (National Survey of Family Income and Expenditure) and nursing care insurance data (Survey of Long-term Care Benefit Expenditures) was conducted. Particularly, we considered the expenses of nursing care insurance to calculate CF in the nursing care sector. The expenses are defined as the costs for the nursing services that consist of the sum of the insurance benefit amount, the public expense amount, and the user-paid amount.

As a result, the CF on nursing care services varied from 117 to 4392 kg-CO_2eq per person per year, depending on the level of nursing care required. Besides, it was found that households with people who are certified for long-term care generated 1.4 times larger CF than households without those people. Regarding the pattern of CF, the largest difference between households with and without people who are certified for long-term care was engendered in the nursing care sector. Additionally, households with people who are certified for long-term care were more likely to generate the CF on goods associated with staying home, such as electricity and gases. The previous studies reported that elderly households would generate lower CF per capita than young and middle-aged households. However, we figured out that the CF would considerably increase regarding both a person who is certified for long-term care in a household and the compensation of nursing care insurance. We also estimated that the CF on nursing care services would reach 16 Mt-CO_2eq (1.3% of total CF in 2020). Conclusively, our results indicate that an increase in people who need more serious long-term care may boost GHG emissions unexpectedly. As Japan's population continues aging, the Japanese government should develop GHG abatement strategies that focus on the nursing care sector. We also note the importance of prevention in nursing care from not only human health but also environmental perspectives and the need to explore mitigation policies that take into account future changes in demographic structure. For future study, it is necessary to consider the welfare instruments and fixed capital related to long-term nursing care in the current analysis.

Avoiding turmoil. Achieving targets. Attempting NetZero: Perspectives from the Water Sector

Monday, 3rd July - 17:45: Footprints 2 (B0.31 KOG)

Anna Christy [1]***, Oliver Heidrich*** [1]***, Marwa Elnahass*** [2]***, Anthony Browne*** [3]***, Jaime Amezaga*** [1]***, Andrew Moore*** [3]

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The last decade is evidence that 'business as usual' means high likelihoods of global temperatures being between 4-5 ºC, above pre-industrial levels by 2100 (Hausfather and Peters, 2020). Now, central and local governments as well as businesses worldwide, are joining the race to NetZero. However, participation in this race has quickly become a necessity not only from a climate action perspective, but also to maintain business reputation, by supplying for consumer demands and meeting regulatory targets. Nevertheless, achieving business targets and attaining a stamp to signify carbon NetZero may not necessarily mean avoiding turmoil.

The English Water sector has been a leader in the race to NetZero, being the world's first to make a sector-wide NetZero commitment (Walker et al., 2021). To support this, water companies in England and Wales use a heavily regulated and annually revised Carbon Accounting Workbook since 2008. Since carbon accounting and reporting has shown to be a catalyst for effective climate action, improving carbon accounting tools can provide tangible evidence to show whether Net Zero is achievable (or not) (Bui and Fowler, 2019).

Therefore, using this sector as a case study, this research has explored 95 articles on carbon accounting and reporting methods using a well-recognised literature review methodology, the Preferred Reporting Items for Systematic review and Meta-Analyses protocol (Moher *et al.*, 2015). We find the current literature presents drastic variations between the international agreements, national legislations, regulations and standards surrounding carbon accounting, meaning they communicate differing methods of best practise. We identify key limitations such as poorly defined best practice trickling down to business-level, through our collaboration with Northumbrian Water Limited (NWL) and propose a new carbon accounting framework.

A novel aspect of this study is that it provides a unique insight into the English Water sector's carbon accounting tool and is the first study to incorporate reflections and real business cases from industry collaborators like NWL, who stands as the main provider of water service provider of the Northeast of England. This research offers key policy implications and recommendations for various sets of stakeholders including regulators, investors and practitioners, for the English Water sector and beyond, to help establish standardised and consistent best practices for carbon accounting.

Bui, B. and Fowler, C.J. (2019). Strategic Responses to Changing Climate Change Policies: The Role Played by Carbon Accounting. *Australian Accounting Review*. doi:10.1111/auar.12213.

Hausfather, Z. and Peters, G.P. (2020) 'Emissions–the 'business as usual' story is misleading'. *Nature Publishing Group*.

Moher, D., et al., (2015) 'Preferred reporting items for systematic review and meta-analysis protocols (PRISMA-P) 2015 statement', *Systematic Reviews*, 4(1), p. 1.

Walker, N.L. et al., (2021) 'Aligning efficiency benchmarking with sustainable outcomes in the United Kingdom water sector', *Journal of Environmental Management*, 287, p. 112317.

EEIOA cases 2

Improving the Sustainability Assessment of the Olympic Games through Environmentally-Extended Input-Output Analysis

Monday, 3rd July - 16:30: EEIOA cases 2 (B0.13 KOG)

Frederike Arp [1], ***Ranran Wang*** [1], ***Tomer Fishman*** [2]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden, 2. CML Leiden

Mega sporting events like the Olympic Games and the FIFA World Cup impact society significantly through various means, including celebrating sport and competition, stimulating socio-economic and cultural exchanges, boosting infrastructural development, and causing environmental impacts. Environmental sustainability in the Olympic Games has gained greater significance since 1991, with the 2024 Summer Olympics in Paris taking the lead by aiming to become the first climate-positive edition of the event.

However, environmental impact assessment of mega events proves to be challenging as no events are alike and are often very complex. Moreover, to verify the sustainability goals, a variety of aspects need to be considered, such as new venue construction and the travels of spectators and participants, and the impacts must be measurable in a comprehensible way. In contrast, the most recent environmental sustainability assessment of the Olympic Games uses only three general indicators (1. Share of newly-build venues, 2. Number of tickets, 3. Number of accreditations), which may not be robust in exceptional situations such as the COVID-19 pandemic (*Müller et al., 2021, Nature Sustainability*). Moreover, the study highlights that the sustainability of the Olympics has been decreasing from 1992 to 2020.

We argue that a comprehensive approach to sustainability assessment of mega sporting events must systematically consider its various environmental implications. As such, this research aims to explore the potential of one of IE's systems analysis approaches - environmentally-extended input-output analysis (EEIOA). Although applying input-output analysis (IOA) for the economic impact evaluation of the Olympic Games is relatively common (*Wood and Meng 2021, Tourism Economics*), EEIOA is rarely discussed and has only been applied once on a small scale to test the method for the assessment of mega sporting events (*Collins et al., 2009, Tourism Management*). The method has the unique niche of integrating economic and environmental accounts, linking almost all types of expenditures of the Olympic Games with the associated environmental impacts incurred along the global supply chain and enables the differentiation between domestic and exported impact.

We intend to contribute to an improved sustainability assessment of mega sporting events. The proposed method can be applied in the future, ex-ante and ex-post, to support the decision-making process, monitor compliance with targets, and improve the sustainability of mega sporting events.

In the presentation, we will present:

1. The state-of-the-art sustainability assessment of mega sporting events and critical limitations
2. Methodological developments and new findings from the Olympic Games case
3. Future opportunities for enhancing environmental sustainability assessments of mega events

Aligning nutrition with planetary boundaries: changing consumption alone is not enough

Monday, 3rd July - 16:45: EEIOA cases 2 (B0.13 KOG)

Martin Bruckner [1]***, Stefan Trsek*** [2]***, Julia Kreimel*** [2]

***1.** ETH Zurich,* ***2.** Wirtschaftuniversität Wien*

Today in Austria, as in many other high-income countries, high-calorie diets with a large share of highly processed and animal-based foods are predominant. Such diets not only promote a variety of diseases, but are also resource intensive. Our food system is, in fact, a major contributor to planetary boundary transgression.

We use the physical multiregional input-output database FABIO to estimate the environmental impacts of food consumption in Austria in 2020, taking into account six planetary boundaries (freshwater use, biodiversity loss, greenhouse-gas emissions, land use, nitrogen and phosphorus application), and compare it with those of the official national dietary recommendations ('Food Pyramid') and the EAT-Lancet Commission's recommendation ('Planetary Health Diet'). We find that the current Austrian diet exceeds five of the six planetary boundaries so much that even the upper limit of the uncertainty zone is transgressed. Animal-based foods, especially meat and dairy, particularly contribute to the transgression of planetary boundaries.

However, following the recommendations of the 'Food Pyramid' or the 'Planetary Health Diet' does not guarantee staying within planetary boundaries either. Instead, most planetary boundaries continue to be exceeded even after substantial dietary changes. One reason is the large share of dairy products recommended by the 'Food Pyramid'. In the 'Planetary Health Diet', increased consumption of nuts and seeds is driving the transgression of planetary boundaries. Furthermore, the consumption of coffee, cocoa, and alcoholic beverages has considerable footprints.

We show that if all animal foods were replaced with plant-based foods, environmental impacts would be reduced substantially and only the lower limit of the uncertainty zone would be exceeded for some dimensions. This shows that a change in diets can make a significant contribution on the way to achieving a nutrition within planetary boundaries, yet changes in food production and land management are essential as well.

Sharing economy rebound: The case of peer-to-peer sharing of food waste

Monday, 3rd July - 17:00: EEIOA cases 2 (B0.13 KOG)

Tamar Meshulam [1]***, David Font Vivanco*** [2]***, Vered Blass*** [3]***, Tamar Makov*** [1]

1. *Ben Gurion University of the Negev,* ***2.*** *ecointelligentgrowth,* ***3.*** *Tel-Aviv University*

The digital sharing economy is commonly thought to promote sustainable consumption and improve material efficiency through better utilization of existing product stocks. However, the cost savings and convenience of using digital sharing platforms can ultimately stimulate additional demand for products and services. As a result, some or even all of the expected environmental benefits attributed to sharing could be offset, a phenomenon known as the rebound effect. Relying on a unique dataset covering over 750,000 food items shared in the United Kingdom through a free peer-to-peer food-sharing platform, we use econometric modeling, geo-spatial network analysis, and environmentally extended input–output analysis to quantify how much of the expected environmental benefits attributed to sharing are offset via rebound effects under seven re-spending scenarios. We find that rebound effects can offset 59–94% of expected greenhouse gas (GHG) emission reduction, 20–81% of expected water depletion benefits, and 23–90% of land use benefit as platform users re-spent the money saved from food sharing on other goods and services. Our results demonstrate that rebound effects could limit the potential to achieve meaningful reductions in environmental burdens through sharing, and highlight the importance of incorporating rebound effects in environmental assessments of the digital sharing economy.

Risk of intact forest landscape loss goes beyond global agricultural supply chains

Monday, 3rd July - 17:15: EEIOA cases 2 (B0.13 KOG)

Siyi Kan [1]***, Bin Chen*** [2]***, Martin Persson*** [3]***, Guoqian Chen*** [4]***, Yutao Wang*** [2]***, Jiashuo Li*** [5]***, Jing Meng*** [1]***, Heran Zheng*** [1]***, Rui Li*** [6]***, Mingxi Du*** [7]***, Thomas Kastner*** [8]

1. *University College London,* ***2.*** *Fudan University,* ***3.*** *Chalmers University of Technology,* ***4.*** *Peking University,* ***5.*** *Shandong University,* ***6.*** *Beijing Forestry University,* ***7.*** *Xi'an Jiaotong University,* ***8.*** *Senckenberg Biodiversity and Climate Research Centre*

Intact forest landscapes (IFLs) have exceptional conservation value considering the range of ecosystem services they deliver. For example, IFLs store much more carbon per hectare than other forest zones (over 3 times higher in Latin America and Africa). Global IFL area reduction has reached 1.5 million km^2 during the last two decades. Related carbon emissions may compromise global net-zero strategies and hinder the implementation of land-based climate solutions.

There is widespread concern about the driving effects of local production (especially agricultural expansion) on deforestation. However, since land-based products are often tied to international demands for food and materials and exported for consumption elsewhere through global supply chains, regional land use change is no longer simply driven by local demand but is rather indirectly influenced by international markets. Such globalization of land use has spurred substantial studies on consumption-side drivers of land use, but none have focused specifically on IFL loss.

In addition to deforestation (i.e., the complete removal of tree cover), forest ecosystems are also facing degradation and fragmentation caused by non-agricultural activities like logging, mining and energy extraction, which often precede deforestation and affect overall forest structure and composition, inducing landscape-scale ecological changes (e.g., tree mortality and biodiversity loss) , increasing vulnerability to external disruption (e.g., fires and wind) and initiating a cascade of land use changes because of easier access to the remaining forests.

Therefore, we focus on IFL loss (including deforestation, forest degradation and fragmentation) caused by various economic activities and investigate the influence of global consumption and trade via the multi-regional input-output model. For IFL loss associated with the 2014 world economy, over 60% was related to final consumption of non-agricultural products. 37% was linked to export production (mostly in Russia, Canada and tropical regions), with mainland China, the EU and the USA as dominant consumer markets. Of overall IFL loss associated with export, 51% and 26% was directly caused by logging and mining/energy extraction, respectively. **Compared to agriculture-dominated deforestation, the much more dispersed nature of IFL loss drivers and its more indirect links to individual final consumers call for stronger government engagement and supply-chain interventions. Moreover, since metals and minerals play an important role in the ongoing global transition towards a green energy system (e.g., lithium, nickel, cobalt and graphite are crucial to battery performance), threats from mining and energy extraction deserve special attention.**

A model to assess the environmental, social, and financial performance of reusing buildings services

Monday, 3rd July - 17:30: EEIOA cases 2 (B0.13 KOG)

Sébastien Loreau [1], ***André Stephan*** [1], ***Daniel Cooper*** [2], ***Anne-Laure Maerckx*** [3]

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An increasing number of cities are promoting reuse as a key strategy in the transition towards a more circular economy in the construction sector. In Brussels, Belgium, building services (i.e., plumbing, heating, cooling, ventilation, and electrical services) are seen as one of the most important building elements to consider in the implementation of this new type of economy. However, the reuse of building services is still not common practice. One of the obstacles is the lack of knowledge about the performance of this practice. This study aims to bridge this gap by developing a model to assess the environmental, social and financial performance of reusing building services products. The development of the model relies on several steps, of which the following are within the scope of this conference: the definition of system boundaries, and the selection of indicators and quantification methods for the environmental and social dimensions.

System boundaries are defined based on a literature review. The resulting system boundaries differentiate between two scenarios, i.e., the reuse of a product and its replacement with a new equivalent product. The reuse scenario includes a careful dismantling of the product, its transport to a repair facility, its repair, and its use in the building. The replacement scenario includes a standard dismantling, its transport to a recycling facility, the manufacturing of a new equivalent product, and its use in the building with a potentially higher water/energy efficiency for a potentially longer period.

Environmental indicators are selected based on a literature review. The resulting environmental indicators are *climate change*, *primary energy use*, and *freshwater use*. *Climate change* is a critical environmental impact indicator given the climate emergency. *Primary energy use* is a good proxy for other environmental impacts. *Freshwater use* does not correlate well with *primary energy use*. The quantification method is selected based on an analysis of all available environmental datasets for a 500 kW chiller. The resulting quantification method is to take indicator values directly from generic datasets (e.g., datasets provided by INIES). This is because generic data tend to be overestimated when compared to specific data, which makes it the safest data source. However, indicator values related to repair activities are often unavailable from generic datasets, therefore, these are calculated by mass ratio according to the components to be replaced.

Social indicators are selected based on a correlation study between the 56 indicators available in the PSILCA database, and a social hotspot analysis within the PSILCA database for the sectors manufacturing and repairing chillers for the Belgian market. The resulting social indicators include *work hours*, *fatal accidents*, and *association and bargaining rights*. *Work hours* is a good proxy for other social impacts. *Fatal accidents* does not correlate well with *work hours*. *Association and bargaining rights* shows abnormally high values for the sectors manufacturing chillers for the Belgian market. In addition, a fourth indicator is included, i.e., *contribution to economic development* because it is a critical social impact indicator given its close link with local policy. The selected quantification method is to take indicator values from the PSILCA database and use structural path analysis to detail each sector's contribution along the supply chain.

It is critical to develop more comprehensive approaches to the evaluation of reuse practices to ensure life cycle performance across different dimensions, beyond tunnel visions focusing on single indicators.

European Green Deal: The road to the European clean energy transition could be paved with its critical mineral resources

Monday, 3rd July - 17:45: EEIOA cases 2 (B0.13 KOG)

Etienne Berthet [1], ***Julien Lavalley*** [1], ***Candy Deck*** [2], ***Fernanda Sophia Ballesteros*** [3], ***Konstantin Stadler*** [2], ***Ugur Soytas*** [1], ***Michael Hauschild*** [1], ***Alexis Laurent*** [1]

1. *Technical University of Denmark,* ***2.*** *NTNU,* ***3.*** *Deutsche Institut für Wirtschaftsforschung*

Our study discusses the challenges posed by the limited availability of critical minerals needed to achieve net-zero greenhouse gas emissions by 2050 in the European Union (EU) in the context of the European Climate Law and the "Fit for 55" package. We argue that the EU must undertake a comprehensive assessment of the social and environmental impacts of critical mineral extraction and processing to ensure secure and sustainable access to these minerals. We used the Economic-Environmental Input-Output (EE-MRIO) EXIOBASE to perform this social impact assessment. We fully updated the EXIOBASE social satellite accounts with the latest data from the International Labour Organization (ILO).

Then, among the social impacts, our study argues that the Green Deal's goal of social fairness may be compromised by exposing up to 90,000 mining workers worldwide to the risk of modern slavery due to increased demand for critical minerals required for the energy transition. Our study highlights the need to differentiate between ore and mineral extraction when analysing global supply chains. It also identifies bottlenecks in mineral supply and emphasizes the importance of a consumption-based approach to identify hotspots in mineral footprints and associated social and environmental impacts globally.

At a political level, our study argues that EU policymakers must balance mineral production, consumption risks, and benefits. They should diversify EU supply chains of critical minerals by developing intra-European mining activities and enhancing mining regulations in member states. Furthermore, our study emphasizes the importance of promoting investments in the mining sector, showcasing best practices, and improving social acceptance to gain trust among citizens and investors. The study concludes that the EU must consider supply, environmental, and social risks when designing policies dealing with critical minerals to ensure successful implementation and fair global application.

Industrial symbiosis 2

Facilitator functions for knowledge sharing during the emergence of IS networks

Monday, 3rd July - 16:30: Industrial symbiosis 2 (A1.44 KOG)

Katrin Katana [1], ***Besma Glaa*** [1]

1. Linköping University

Industrial symbiosis (IS) is an environmental business practice within the industrial ecology field where traditionally separate entities collaborate to increase resource productivity by exchanging by-products or sharing utilities and services. IS development has gained a following among practitioners and academics alike as it can provide participating organisations with economic advantages by reducing cost or increasing revenue while also contributing to sustainable development by reducing primary resource use, emissions, and waste generation. Many IS scholars agree that knowledge and information sharing have a catalyser role for IS development and have a positive influence and benefits among actors of IS network. Therefore, the practice of IS has increasingly developed beyond physical material and energy transactions to focus more on cooperation through resource, information, and knowledge sharing. To realize these benefits, there is a need for facilitators. Recently, research has highlighted knowledge sharing activities carried out by IS facilitators as crucial for the emergence of IS networks. However, IS facilitation should not be understood as homogenous as the role a facilitator holds within a network is demanding and context dependent. Yet, few researchers investigated this matter in depth and recently there are research calls for this type of studies.

Therefore, this paper draws on network theory to explore how knowledge sharing activities and responsibilities are divided among actors in IS networks as well as the facilitator functions in relation to their organizational characteristics and the network governance for different facilitating contexts. To understand this relationship, we conducted a multiple case study of four emerging IS networks in four different countries.

This study revealed firstly that each IS network needs to adapt a unique information sharing structure, governance style, and responsibility division based on the nature of their own network constellation and needs. For example, while some IS networks should be governed by and through a single organisation that acts as a centralized network intermediary other IS networks should be governed by a joint organisation comprised of representatives from all network actors sharing the network responsibilities or governed by the network actors themselves with no separate governance entity. Secondly, the facilitator functions depend on the network governance form and the facilitator organizational characteristics within an IS networks for different facilitating contexts. Thirdly, ownership over the IS development and the strategic relevance of the IS collaboration influence the network actors' desire to control information flow, their need for information as decision-makers, and their desire to engage in and commit resources to collaborative efforts.

Uncovering industrial symbiosis in the United States: Statistical exploration of the Northeast and influencing factors

Monday, 3rd July - 16:45: Industrial symbiosis 2 (A1.44 KOG)

Koichi Kanaoka [1]

1. Center for Industrial Ecology, School of the Environment, Yale University

The promotion of industrial symbiosis (IS) has been gaining traction internationally as a strategy to stimulate economic growth while limiting environmental impacts, but relatively few IS cases in the United States have been reported. Some scholars speculate that the American businesses culture, still embracing the spirit of rugged individualism, may be incompatible with the collaborative nature of IS. To address these knowledge gaps, I investigate the following questions using statistical approaches: "How prevalent are industrial symbiosis networks in the US, and what factors may be influencing their formation?" This study provides a broad sense of the state of IS—a first of its kind for the U.S.—and brings together the variables previously identified to be important for its development (i.e., economic, social, environmental, and technological) into a single statistical model. Companies indexed in business databases are sampled and surveyed to identify industrial by-product exchanges, in combination with desk research. The regression analysis examines variables related to factors that may influence IS development, such as company characteristics (e.g., revenue, age, industry), geographic density of firms, social networking opportunities, and regulatory environment. The study sites, selected for their comparability and their ease of data acquisition, consist of five states: New Jersey, New York, Pennsylvania, Maryland, and Delaware—states that often are grouped together for their similarities in economic and environmental factors. The results of the exploratory data analysis, along with the dataset itself, could serve as a foundation for conducting studies that evaluate specific causality claims. Such studies may lead to the formulation of effective strategies and policies to promote IS in regions with less-aggressive environmental policies.

Pricing in industrial symbiosis: Challenges and solutions

Monday, 3rd July - 17:00: Industrial symbiosis 2 (A1.44 KOG)

Marianna Lena Kambanou [1], ***Murat Mirata*** [1]
1. *Linköping University*

In the context of industrial symbiosis (IS), some companies exchange underutilized or secondary resources such as waste, by-products, residues, low grade energy, wastewater and greywater. These underutilized or secondary resources differ in terms of physical properties and perceived value compared to goods exchanged on the business-to-consumer or business-to-business markets. Moreover, to facilitate the exchange of such resources, asset specific investments may be required. Collectively these conditions create several challenges for determining the compensation, or pricing formula for the exchanged good or service.

Companies create different pricing solutions to these challenges – yet the details of these challenges and their solutions are rarely documented in literature. This is not surprising as the terms of pricing agreements between firms are agreed upon behind closed doors with neither intermediaries nor researchers present and are often considered confidential.

To improve knowledge on the types of pricing challenges and solutions in operational and developing industrial symbiosis cases, empirical research with 28 interviews covering 52 IS exchanges was conducted. The interviewees explained the terms of the pricing agreements, the challenges they had encountered and the solutions on the highest level of detail they could without breaching confidentiality. In an iterative process involving both authors, the analysis sought to identify categories of challenges and link them to a variety of solutions. The following main challenges were identified:

1. Quality and quantity of residuals are unstable and can fluctuate.
2. The supplier has a legal obligation to safely manage residuals.
3. While production costs of residuals are typically covered by the sales of primary products, making them usable incurs additional costs.
4. IS relationships often have high transaction costs.
5. IS delivers diverse values to the parties involved.
6. Residuals may lack comparable market prices.
7. Costs of alternatives are dynamic.
8. IS partners often have diverse backgrounds.
9. Investments are upfront and can be significant.
10. Asymmetrical investment distribution between partners.
11. Power asymmetries between partners.
12. Difficulty with ex-ante performance assessment.
13. Dynamic nature of conditions.

For each of these challenges several solutions were also identified. For example, “residuals may lack comparable market prices” can be solved by agreeing upon a pre-determined calculation which pegs part of the agreed price to an index or an array of goods. Another solution to this challenge is to add price ceilings, price floors or price renegotiation clauses in the agreement. Finally, some companies solved this challenge by making “ the user’s sale price” a factor in the pricing agreement.

These findings make a significant contribution to researchers’ understanding on the conditions and terms surrounding the pricing of IS exchanges and contributes to practice by providing both industry and intermediaries with an array of proven solutions to common challenges. Neither the challenges nor the solutions can be considered exhaustive as they are limited to European cases.

This research is part of the project “Creation Of new value chain Relations through novel Approaches facilitating Long-term Industrial Symbiosis” (CORALIS) and has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No 958337.

Waste inventory for industrial symbiosis: is it worth it? An Enterprise Input-Output approach

Monday, 3rd July - 17:15: Industrial symbiosis 2 (A1.44 KOG)

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This paper investigates the strategy of resource stocking in industrial symbiosis – a manifestation of the broader concept of the circular economy (Domenech and Bahn-Walkowiak, 2019; Merli et al., 2018) – where companies use waste(s) from different industries as a substitute for traditional input materials (Chertow, 2000). As the waste is not produced upon demand but appears as a secondary output of another production activity, mismatch between waste supply and demand is mostly unavoidable (Fraccascia and Yazan, 2018). This paper aims at contributing to a solution of the supply-demand mismatch by investigating the benefits of a waste inventory strategy. Inventories are traditionally used by companies as a tool to balance demand and supply levels of resources, and to cope with disruptive events affecting supply chain members (e.g., failure rates, unavailability of production plants, delays in transportation, etc.) (Dolgui and Ivanov, 2020; Tang et al., 2021). However, holding inventory requires additional space and creates additional costs for companies, e.g., due to storage, obsolescence, damage risk, deterioration, shrinkage, insurance, and management costs, as well as the more traditional cost of capital invested (Christopher, 2016). Hence, the higher the amount of inputs stocked, the more companies are protected against uncertainties in the supply chain, but also the higher the inventory costs will be, ceteris paribus. In the IS context, companies may keep a safety stock of wastes and use it when the potential supply becomes lower than the demanded amount. However, the practice to stock wastes is hardly adopted by companies involved in IS synergies.

This paper is thus aimed at: (1) investigating whether and in which conditions the economic advantages provided by the practice of stocking wastes are higher than the burden of keeping inventories; (2) assessing the additional environmental benefits created thanks to industrial symbiosis when companies adopt waste inventory practices. An enterprise input-output model is designed that models the waste inventory strategy and a numerical case, based on discrete event simulation, is used to show how the model works. In particular, the impact of the following variables on the waste inventory strategy is investigated: (1) environmental dynamicity, i.e., the size of fluctuations in waste production and demand; (2) magnitude of safety stock of wastes; (3) unit inventory holding cost; and (4) unit fixed inventory cost. 135 scenarios are investigated from the numerical perspective. Results indicate that stocking wastes is always useful from the environmental perspective, while waste market dynamicity, inventory magnitude, and unitary costs to stock waste are critical factors that determine the economic feasibility of inventories in an industrial symbiosis business case.

A location-based optimization model for development of agricultural greenhouses running by waste heat of industries to practice industrial symbiosis

Monday, 3rd July - 17:30: Industrial symbiosis 2 (A1.44 KOG)

***FARZANEH REZAEI* [1], *Stephan Pfister* [2], *Vanessa Burg* [3], *Stefanie Hellweg* [2], *Ramin Roshandel* [1]**

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Utilizing the waste heat of industries to meet the heating demand of agricultural greenhouses can mitigate their environmental impacts, as greenhouse cultivation is one of the energy-intensive agricultural sectors. We developed a location-based optimization model with an economic-environmental objective function (minimization of total annual cost and impact) for identifying optimal industrial symbiosis opportunities between greenhouses and target industries for an industrial region as a case study. In the first step, geographical analysis is employed to identify suitable lands (agricultural land areas which are close to industrial plants) for developing greenhouses. Then, considering location attributes and crop type, the heat demand of greenhouses that may be developed on those lands is estimated. Finally, the optimization model is integrated with a geographical information system (for extracting data including distance between industries and greenhouses or the areas of candidate lands) and the results of the optimization are displayed as opportunity map which determines the optimum greenhouse area supplied by the waste heat from industries. In addition to simple heat transfer by pipeline, organic Rankine cycle (ORC) is considered as a technology to generate electricity and heat to greenhouses (in cases where waste-heat temperatures allow for the use of ORC). Results show that the distance between greenhouses and industries, the specific heating demand of greenhouses and the cultivated crop affect the optimal location of greenhouses. Furthermore, when including the “economy of scale” (i.e. unit investment cost decreasing with increasing output) leads to prioritizing large-scale greenhouses (minimum 20 hectares).

Untangling spatiotemporal generation and recycling of solid waste in China's coal-fired electricity sector

Monday, 3rd July - 17:45: Industrial symbiosis 2 (A1.44 KOG)

Hanbo Gao [1], ***Yang Guo*** [2], ***Haozhi Xu*** [1], ***Jinping Tian*** [3], ***Lyujun Chen*** [3]

1. Tsinghua University, 2. Princeton University, 3. School of environment, Tsinghua University

Introduction

According to China's energy endowment of "rich in coal, poor in oil and little in gas", coal-fired power has played a significant part in Chinese social economic system. After the national pledge of carbon peaking before 2030 and carbon neutrality before 2060 (dual-carbon strategies), the country is stressing the cornerstone role of coal in the domestic energy system, based on its clean and effective utilization. Since 2005, emission standards of coal-fired power plants have been improving continuously, and therefore air pollution fulfilled remarkable decline. However, longstanding air-to-solid burden shift and resulting solid waste stocks with cleaner flue gas in coal-fired electricity sector have strikingly obstructed sustainable energy development.

Methodology

Building material production is seen as a promising pathway to digesting the coal waste. Targeting the challenges of insufficient land resources and lack of solid waste scavengers in coal-fired power plants, this study profiles a source-sink panorama of coal power solid waste in China from 1970s-2050. Here we uncover the spatiotemporal heterogeneities of solid waste generation including fly ash, bottom ash and flue gas desulfurization gypsum using a unit-specific geodatabase and material flow analysis. We then quantify their recycling potential and associated environmental benefits through plant-level cement producer database, multi-objective optimization model, and life-cycle assessment. Different retirement schedules for the coal power plants and uncertainty analyses are deployed to ensure the result robustness.

Results and Discussion

Cumulative generation and stocks of coal power solid waste are 5.8 and 1.8 gigaton (1.3, 0.3 and 0.2 gigaton of fly ash, bottom ash and FGD gypsum), respectively, during 1975-2020, totally equal to six times industrial solid waste stocks of China's cities in 2019. We estimate that 4.0-8.0 gigaton of coal power solid waste will be generated till 2050, based on various retirement schedules for coal power generation units. Current inadequate linkage between coal power and building material sectors hinders the solid waste utilization. The feasible transport radius of solid waste from coal power to cement plants without additional economic cost and environmental pressure can reach 397.2 km. Accordingly, cross-sector collaboration between coal power and building materials can recycle 3.2-6.6 gigaton of solid waste during 2020-2050, and deliver 1.2-2.6 gigaton CO_2 equivalent of carbon mitigation, 1.4-2.8, 0.9-1.9 and 1.5-2.9 megaton of SO_2, NO_x and $PM_{2.5}$ emission reductions, and 1.7-3.4 billion m^3 of water savings. Tailored policies should foremost focus on northwest and north provinces which generate most of the solid waste, and target fly ash in priority to be recycled in building material production. Technical standards and economic incentives should be formulated for coal waste being recycled in building materials. Additionally, a whole-process information platform of coal solid waste from generation to disposal could be built, encouraging enterprises to set up a third-party waste disposal company for promotion of the optimal economic-environmental waste producer-scavenger matching from a global and systematic perspective.

Vehicles

An ethnography of the automobile: A participatory tool for understanding human behavior in automotive recycling context

Monday, 3rd July - 16:30: Vehicles (B0.16 KOG)

Veronica Davidov [1], ***ivan cukeric*** [2]

1. Monmouth University, 2. Edgeryders OU

As industrial ecology contexts sit at the intersection of nature, culture, and economics, an anthropological approach to human behavior in industrial ecology can offer a holistic perspective designed to surface hidden assumptions and biases.

This abstract represents the results of the first phase of a mixed methods (ethnographic interviews and semantic network analysis) study of the circular economy in the automotive industry.

Methodologically, it is a proof of concept that such a mixed-methods approach can be a valuable tool for making the management and governance of recycling related practices in the automotive sector more inclusive and effective.

This study centers around interviews in an "event ethnography" setting. In the mixed-methods tradition, ethnographic data yielded by the interviews is transcribed and semantically coded; the codes are expressed as a network of co-occurrences. The network is then analyzed, reduced and visualized, using techniques from network science. The combination of two methods allows us to see not only what people are saying, and how they are saying it, but also explore what things are mentioned together by the same people, identify areas of broad consensus, and overall produce a conceptual map of constituent perspectives around circular economy and sustainability practices in the automotive. Our data set consists of 111 interviews across 5 car industry events. The interviews yielded 285 semantic codes, which visualized were shown to be connected by 11,468 co-occurrence edges, including 3,999 unique co-occurrences.

Industrial ecology investigates the circulation and flow of industrial materials in and out of the natural environment as a result of human activities. We found that there is a pervasive ambivalence about car electronics stemming from the different sensory and interactive experience between a human and a car depending on the different physical possibilities of the industrial materials involved in car manufacturing (including issues of privacy and surveillance and their impact on user acceptance of sustainable technologies). This finding is highly relevant for the topic of human behavior in the industrial ecology context, as it offers insight into sustainable behavior pertaining to consumer and citizen choice in the car sector.

The specific insights yielded by visualizations, which help to inform future research into human behavior in industrial ecology contexts, include:

- There is an under-recognition of the concept of "circular economy" in the general public that is interested in cars; to the extent that there is awareness of this concept, people primarily associate it with concrete material practices (recycling behavior, parts modification, parts repurposing) more so than an ideological vision.
- Personal networks of knowledge and expertise built around trust are linked to the practices of car maintenance, and, therefore, are important to consider for industrial ecologists focused on human behavior.
- There is a high degree of conditionality in people's narratives of their behavioral choices, i.e. hypothetical scenarios, considerations and deliberations that social actors engage in when making decisions that can contribute to (or work against) sustainable initiatives, such as participating in a circular economy of the automotive industry. Scholarship on human behavior in industrial ecology should be attuned not only to reported behavior, but also to hypothetical scenarios such as "I would do X under these conditions"

or "If it weren't for Y, I might purchase this kind of car."

US-Mexico Second-hand Vehicle Trade: Implications for North American EV circularity, infrastructure and regional policy

Monday, 3rd July - 16:45: Vehicles (B0.16 KOG)

Francisco Pares Olguin [1], *Galym Iskakov* [1], *Alissa Kendall* [1]
1. University of California, Davis

The US is rapidly increasing electric vehicle (EV) sales to meet decarbonization targets for the transport sector. Assessments of life-cycle environmental impacts of EVs have uniformly assumed that vehicles purchased in the United States (US) stay in the US for their entire life cycle, yet the US exports close to a million used cars annually, primarily to lower and middle-income countries. Considering the dramatic increase in demand for EVs projected for the US in the coming decade, as the fleet ages, we expect EVs to enter international second-hand (SH) vehicle markets.

It is still unclear whether these exports will confer environmental benefits on receiving countries, particularly when considering extended use, the electricity grids used to charge them, local maintenance and repair practices, and available end-of-life (EOL) management systems for EV batteries. Concurrently, exported SH vehicles could reduce the potential circularity of domestic EV battery production via lost secondary material recovery.

According to data provided by the National Customs Agency of Mexico (ANAM), Mexico is historically the largest SH vehicle export market for the US. Between 2005 and 2022, the country imported nearly 9 million used vehicles from the US, representing approximately 30% of Mexico's current total in-use vehicle stock of around 30 million.

Using system dynamics modeling and life cycle assessment (LCA), this research develops scenarios for future SH vehicle trade dynamics between the US and Mexico to anticipate the flow of SH EVs and implications for (i) the environmental life cycle performance of EVs sold in the US but traded to Mexico, (ii) the infrastructure required to safely and effectively manage EOL EVs in Mexico, (iii) the estimation of critical battery material flows out of the US, and (iv) policies and regulatory instruments that could be implemented in North America to ensure continuity of SH vehicle markets while reducing environmental burdens and maximizing economic benefits to the region.

Initial results show that as the share of EVs in the US reaching the average age range for exports increases, Mexico will begin recording SH EV imports at a rate of 1-2% out of nearly 200,000 per year in the second half of the 2020s. This rate will continue to increase slowly and erratically as more export-age EVs become available in the US. However, driven by Mexico's National Electric Mobility Strategy, demand for new EVs in Mexico is expected to take off by the mid-2030s, indicating that enough cultural acceptance and legislative, financial, and technical infrastructure will likely be in place to support the sustained growth of a SH EV market. As a result, Mexico will begin experiencing SH EV import rates of 7-39% of total SH vehicle imports, steadily increasing to 84-99% by 2050.

While our work focuses on the case of US-Mexico trade, the US also exports many vehicles to other low and middle-income regions. As such, our modeling approach and findings are transferable to other SH vehicle trade relationships, providing a deeper understanding of the implications of the nascent global SH EV trade.

Decarbonising vehicle fleets - the case for hydrogen

Monday, 3rd July - 17:00: Vehicles (B0.16 KOG)

Simon Edwards [1], ***Philip Blythe*** [1]
1. Newcastle University

The transport sector needs to deliver large emission reductions to achieve carbon neutrality. It contributes 24% of global CO_2 emissions, of which 74.5% is from road vehicles, with passenger vehicles contributing 45.1% and heavy goods vehicles 29.4%[1]. In the UK, transport was responsible for 27% of greenhouse gas emissions in 2019. Of this, 55% was from cars, 16% from HGVs, 16% vans, and 3% buses[2].

The only way for carbon neutrality to be achieved is through adoption of alternative fuels. A range of fuel options is essential, as there is a wide variety of transport modes with different requirements that need to be decarbonised. One such fuel option gaining credence is hydrogen produced from low carbon sources, which can be used directly in internal combustion engines (ICEs), in fuel cells to supply electricity, or as a feedstock to produce other green energy vectors.

For many fleet operators in the transport sector, replacement of vehicles with fuel cell technology is an expensive solution. There are also environmental disbenefits attached to scrappage of existing fleets and manufacture of replacement fleets, which impact on whole life cycle costs. The retrofitting of conventional internal combustion engines (H_2-ICEs) to run on hydrogen can eliminate pollutants including GHGs, CO and NOx. The main modifications to the vehicles involve hydrogen storage in the vehicle and integrating gas injectors into the engine.

One such fleet operator is the UK's Ministry of Defence (MOD). The VITAL project (Defence Innovation Fund, 2021-24) is developing a sustainable Living Lab at RAF Leeming in the North Yorkshire region with its partners RAF Leeming and Newcastle University. The key goal of ViTAL is to identify solutions to decarbonise the airbase. To achieve this, the VITAL project team is exploring the role new energy vectors, including hydrogen, could play. ViTAL links closely with the Tees Valley Hydrogen Hub project (Innovate UK, 2021-22) centred on the nearby location of Teesside. This initiative brings together ULEMCo, RAF Leeming, Tees Valley International Airport, Newcastle University and Emission Analytics to convert a diesel airside tow tug vehicle (SCHOPF MATT tractor) to an electric hybrid H_2-ICE, proving the technological concept and quantifying the elimination of tailpipe emissions of diverse pollutants (utilising PEMs equipment) whilst demonstrating replication of real-world duty cycles.

This paper presents preliminary findings of the Tees Valley Hydrogen Hub project, which suggest that retrofitting conventional ICEs to run on hydrogen may be a viable solution, at least in the short to medium term. Moreover, the technology could be important in establishing a demand for hydrogen, offering a potentially cost-effective route to zero tailpipe emissions through retention of existing vehicle fleets without adversely affecting duty cycles. Stimulating demand for hydrogen in this way could serve to make other hydrogen technology, such as fuel cells, more economically viable. Such an interim and cost-effective solution will still contribute to decarbonisation targets through reducing tailpipe emissions and may be the most viable solution for fleet operators such as the MOD.

The paper also outlines proposed future research looking at retrofitting larger engines synonymous with the MOD's 'green fleet' and heavy goods vehicles used in the haulage, construction and agriculture industries.

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[2] DfT (2021), Decarbonising Transport: A Better, Greener Britain, London: Department for Transport

End-of-Life Lithium-Ion Battery Management Including Safety Perspectives

Monday, 3rd July - 17:15: Vehicles (B0.16 KOG)

Atsushi Terazono [1]***, Masahiro Oguchi*** [1]***, Hiroyuki Akiyama*** [2]***, Hiromitsu Tomozawa*** [2]***, Toru Hagiwara*** [2]***, Miyuki Shintomi*** [3]***, Shingo Kano*** [3]***, Jo Nakayama*** [4]

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In recent years, lithium-ion batteries (LIBs) have been the cause of an increasing number of fires and ignitions at municipal waste management facilities and small home appliance recycling facilities in Japan. In this study, we will conduct surveys and case studies of accidents involving end-of-life LIBs and compare and evaluate management methods in Japan and the EU in order to explore how end-of-life LIBs should be managed, including safety assurance and resource recovery.
First, a survey conducted by the Ministry of the Environment in FY2021 found that more than 11,000 accidents such as fires caused by rechargeable batteries at municipal waste management facilities occurred annually. The authors also found that in some municipalities there are more than 0.1 incidents of ignition or fire per ton of non-combustible and bulky waste. Real-time monitoring using infrared thermography cameras and other equipment was conducted during the crushing process of non-combustible and bulky waste to confirm the situation of LIB ignition. The amount of damage to municipal waste management facilities has been increasing, with the amount of damage estimated to be approximately 3.52 billion yen (25.1 million euro) in FY2021 (average 153 million yen / 1.09 million euro, maximum 860 million yen / 6.14 million euro) based on calculable direct costs alone. If indirect costs are included, the amount of damage could be even larger and the cost of countermeasures could also be significant.
Next, we assessed that there are significant differences in the way end-of-life batteries are managed between Japan and the EU. The collection of end-of-life batteries in Japan differs depending on the type of battery. Small rechargeable batteries, including LIBs, are collected voluntarily based on the Law for Promotion of Effective Utilization of Resources, but there is no target for the collection rate, and large fraction of them are disposed of by local governments. On the other hand, the EU Battery Directive introduced the concept of extended producer responsibility, and the draft of the new battery regulation is considering measures for a circular economy, such as reducing environmental and social impacts, responsible procurement, and ensuring safety throughout the battery life cycle. Although the management of end-of-life batteries is often evaluated from the aspect of resource recovery, it is also considered significant to improve safety assurance as well as resource recovery by reducing the ratio of LIBs mixed in non-combustible and bulky waste through appropriate management based on extended producer responsibility.

CIRCULAR ECONOMY IN CAR ELECTRONICS - A CASE STUDY OF THE COMBIMETER AND THE INFOTAINMENT OF THE SEAT LEON II MODEL

Monday, 3rd July - 17:30: Vehicles (B0.16 KOG)

***Abel Ortego* [1], *Alicia Valero* [1], *Antoinette van Schaik* [2], *Marta Iglesias* [3], *Markus Reuter* [4], *Samuel Alcoceba Pascual* [1]**

1. CIRCE Institute – Universidad de Zaragoza, Spain, 2. Material Recycling and Sustainability (MARAS), 3. SEAT S.A & Sostenipra Research Group (SGR 01412), Institut de Ciència i Tecnologia Ambientals ICTAUAB (MDM20150552), 4. SMS-Group GmbH

A conventional car requires almost 50 elements in its manufacturing, many of which critical from supply risk, geological availability or economic dependence point of view. However, excluding iron, aluminium and copper, together they constitute less than 1% of the total metallic weight of the car. Nonetheless, at the end of life (EoL) a car only steel, aluminium and copper are usually recovered, after shredding and basic physical treatment. Minor but critical elements, used to manufacture electronic components such as combimeters, displays, sensors or LEDs, become either downcycled in low-quality alloys or landfilled, as there are no specific focus in the conventional, shredding driven approach to recycling to recover them. Thus, there is an urgent need to change the car electronic´s design and recycling model to ensure that all metals are used efficiently.

This paper analyzes the loss of mineral capital associated with the car electronics' EoL through the thermodynamic rarity indicator. This indicator considers the scarcity of the minerals in the earth's crust needed to obtain the commodities, as well as the energy required for their extraction and refining. In addition, this paper analyzes the recovery of resources in car electronics considering the modular disassembly based approach to recycling as defined in this work. for different recycling processing routes, which are suitable for recycling these car electronic partsare carried out. Thus, Recycling/recovery rates for each of the commodities are calculated by the application of advanced recycling process simulation models, which in fact virtually design or digitally twin the metallurgical and/or other final treatment processes which are best applied to optimize recycling of the contained materials and compounds.

Moreover, this work assesses the importance of the disassembly of the car parts into different material groups or fractions to improve recyclability. A close link is made here between disassembly analyses and material (in)compatiblities in (metallurgical) processing options and know-how as captured by the developed recycling simulation models.This aspect is very relevant since disassembly processes are associated with high personnel costs, which may not be justified by a moderately higher recovery rate of raw materials at the car's EoL.

As a case study, the combimeter and the infotainment of a SEAT Leon II have been analyzed, since both electronic parts are among the most critical ones in a conventional car considering the contained metals and their low functional recycling.

The recovery rate of the metals included in the selected electronic car parts is assessed for different recycling processing routes and disassembly options: (1) A valuable electronic car part is shredded together with the whole vehicle; (2) It is disassembled from the car and recycled in a metallurgical process specifically designed for the recovery of copper and compatible metals; and (3) In addition to being disassembled, it is sub-disassembled to obtain ferrous and non-ferrous (PCB based) fractions, which are recycled through metallurgical processes designed for recovering steel and copper (including all related elements), respectively.

Our results show that, considering the physical quality of the metals through the thermodynamic rarity indicator mentioned above, the recyclability of the combimeter increases from <0,1% to 59%. Thus, the recyclability potential of car electronics could be further improved in a large extent adopting this three-fold approach, by combining the thermodynamic rarity indicator with the disassemblability and recyclability assessments.

Energy Systems 2

The Change in Electricity Demand Structure after the COVID-19 Pandemic in the Greater Tokyo Area

Monday, 3rd July - 16:30: Energy Systems 2 (B0.17 KOG)

Yuki Hiruta [1], ***Naho Yamashita*** [1], ***Hiroaki Shirakawa*** [1], ***Hiroki Tanikawa*** [1]

1. Nagoya University

The energy system is profoundly affected by the COVID-19 pandemic globally, and the electricity sector plays an important role in the decarbonization process. It is essential to comprehend the effects of pandemic-induced alterations in human behavior and society on electricity demand to prevent an increase in GHG emissions and energy insecurity in post-COVID society. Although electricity consumption appears to be returning to pre-pandemic levels, the underlying structural changes in electricity demand caused by the pandemic remain uncertain. This study aims to detect pandemic-induced structural changes in electricity demand by examining the impacts of the pandemic on hourly electricity demand in the Greater Tokyo Area.

Building a precise model that reflects the true underlying systems driving electricity demand is essential for the purpose. We model the dependence of hourly electricity demand on multiple meteorological and human behavior indicators. Nine models (m17,…, m22; mBC; mAC; mALL) were constructed using the Multivariate Adaptive Regression Splines (Friedman,1991) based on data from different time frames: the individual years from 2017 to 2022, the period before the pandemic (BC, 2017-2019), the period after or during the pandemic (AC, 2020-2022), and all six years combined (ALL, 2017-2022) respectively. The accuracy and robustness of the nine models were thoroughly evaluated using random resampling techniques. After examining the residuals and evaluation metrics based on cross-period validation, the explanatory variables observed in 2020-2022 were applied to the mBC to estimate electricity demand under the hypothetical scenario in which there was no pandemic during 2020-2022 (-pandemic). The difference between the actual demand during 2020-2022 (+pandemic) and the -pandemic was then assessed as the impact of the pandemic. TRFs (temperature response functions) were also simulated for each of the nine models by controlling for the influence of other meteorological and human behavioral factors, to understand the isolated relationships between temperature and electricity demand.

The out-of-sample evaluation metrics, which were based on half of the observations (not used for model training and obtained through random sampling), showed high robustness in the constructed models with R2 ranging from 0.922 to 0.948, MAPE from 3.4% to 4.5%, and RMPSE from 4.6% to 5.9%. The cross-period validations showed that all models constructed based on observations before the impact of the pandemic were interchangeable in estimating demand during 2017-2019, meaning that all models are robust enough to make nearly identical estimations for any observation before the pandemic.

Even after controlling for differences in meteorological factors, the hourly impacts of the pandemic were still shown to be dependent on both hour and season. The residuals between the observed values after the pandemic and the estimated values based on the BC models (m17, m18, m19, and mBC) exhibited an asymmetrical distribution. The comparison of the daytime TRFs before and after/amid the pandemic showed that demand decreases at moderate temperatures (around 13.9°C to 29.4°C) and increases at higher and lower temperatures. These results suggest that even though overall electricity consumption has returned to pre-pandemic levels, the changes in demand structure caused by the pandemic's impact on human behavior and society have been persistent.

Further analysis should be conducted incorporating variables related to the pandemic, such as teleworking levels, to gain a more nuanced understanding of the changes in the demand structure. This will aid in the development of a new normal aimed at reducing GHG emissions and energy insecurity.

Are global net-zero proposals feasible, given the limited availability of key Zero-Emissions Resources?

Monday, 3rd July - 16:45: Energy Systems 2 (B0.17 KOG)

Jennifer Hawkin [1], *Julian Allwood* [1]
1. University of Cambridge

The accumulated demand for global zero-carbon energy resources is unquantified, and supply is unlikely to meet demand.
To address climate change, governments and industries have developed net-zero emissions strategies to guide future investment and policy decisions. However, the literature demonstrates three major shortcomings:

- The first is that business and sector net-zero proposals are each considered in isolation, and their accumulated fundamental resource demands are not quantified.
- Secondly, the plausibility of implementing large-scale energy infrastructure, new technologies, and negative emissions is mostly not considered. Mander et al. observe that the scale or rate of change is generally included only implicitly within models, such that they rely on "unprecedented optimism" (2017). An industry-led report highlighted Carbon Capture and Storage (CCS), Hydrogen and energy storage as problematic, noting that the Climate Change Committee's 2050 proposal bases 40% of our power on these technologies although the current build rate is zero (SNC-Lavalin & Atkins, 2019). Although this issue has been identified, the overall impact on proposals has not been quantified.
- Lastly, it is not clear that there would be sufficient available resources to support published net-zero strategies. Most proposals rely on large-scale use of energy-intensive negative emissions technologies, and technology substitutions, which do not require change at a societal level. The Low Energy Demand (LED) scenario demonstrated that it is feasible to achieve climate goals without relying on negative emissions by projecting the lowest conceivable demand (Grubler et al., 2018) but did not directly challenge alternative high demand proposals. The alternate approach, developing plausible scenarios given available resources and feasible rates of implementation has not been undertaken.

A linear framework can offer insight into the accumulated demands and key constraints.
This study develops a simple linear framework to address these limitations by quantifying the total energy resources implicitly demanded by global proposals. All end-use services (across all sectors) in a hypothetical net-zero world are provided by a combination of different modes (such as battery-electric or hydrogen-powered car transportation), each of which is described by a set of coefficients. Coefficients represent the amount of a given resource required to provide one physical unit of each mode of service and are derived from literature. The demand for end-use services is derived from existing net-zero proposals and is used to scale the resource coefficients.
The final demand is given in terms of Non-Emitting Electricity, Biomass, and Carbon Storage; considered here as the key Zero Emissions Resources since they can produce all other energy carriers but cannot be produced without losses from any other quantifiable source. Comparison of the total demand against realisable rates of supply shows that supply of services is likely to be severely constrained; resource efficiency strategies and novel business models could help close this gap.
The framework also enables further research in the form of attainability analysis, as suggested by Grubler et al. (2015). Overall, the work can contribute to robust decision-making in industry and government and facilitate the development of implementable proposals to achieve net-zero ambitions.

Aligning policy responses to rising energy prices with the long-term climate neutrality objective

Monday, 3rd July - 17:00: Energy Systems 2 (B0.17 KOG)

Edgar Hertwich [1]

1. *Norwegian Univ. of Science and Technology*

Three false narratives cloud our understanding of Europe's energy supply crisis and its relationship to climate policy. These narratives have influenced the crisis response and are today contributing to higher energy prices and greenhouse gas emissions than without. My analysis builds on work done in the development of an advice of the European Science Advisory Board on Climate Change on the crisis, but my argument goes beyond it. The first false narrative is that the ongoing transition away from fossil fuels contributed to the crisis. I show that without the transition, Europe would have been more exposed to Russian blackmail. Unfortunately, we now risk an overinvestment in LNG supply infrastructure which will be unusable without long-term contracts for US shale gas which EU companies do not want to sign. The second false narrative is that energy markets contributed to the crisis and made its social impacts worse. This narrative has most affected European government positions which are grossly interfering in the market, a reaction that is costly and unproductive. I show that the market response has brought prices down again and that market interference was a harmful, expensive political play for the gallery. The third false narrative concerns nuclear power. The mismanagement and early retirement of existing nuclear power plants contributed substantially to the electricity shortage. A lifetime extension of these power plants could reduce the EU's GHG emissions over the coming decade substantially. Nuclear risks are misperceived. Assessments by the United Nations Scientific Committee on the Effects of Atomic Radiation indicate that even under worst case assumptions, the health impacts of past nuclear _*accidents*_ have been comparable to those arising from the _*operation*_ of coal fired power plants and that overall, nuclear power has much lower environmental externalities than fossil power. An invigorated program of more energy efficiency and demand reduction, electrification and a build-out of renewables, and a continued utilization of nuclear assets gives Europe the best chances to bring prices down, reduce greenhouse gas emissions, and secure energy supply with lower geopolitical risks.

Optimization of Regional Cooperation Among Municipalities for Renewable Energies in Japan

Monday, 3rd July - 17:15: Energy Systems 2 (B0.17 KOG)

Takahiko Date [1], ***Kiyo Kurisu*** [1], ***Kensuke Fukushi*** [1]

1. *The University of Tokyo*

Prime Minister Suga at the time of Japan declared at the extraordinary Diet session on October 26, 2020, that it would aim to become “Carbon Neutral” by 2050, and over 800 municipalities in Japan have announced that they will achieve net zero CO_2 emissions by 2050.

“Think globally, Act locally” in Agenda 21 (1992) and “Local authorities have the capacity to solve some of the global environmental problems” in the Aalborg Charter (1994) as stated, it is important to take local actions against global warming.

In recent years, multiple municipalities have started cooperating to supply local renewable energy to cities with high demand. However, these efforts are sporadic, and there has been no discussion of what kind of regional cooperation would be effective for Japan as a whole.

Therefore, considering the power demand of each municipality, the supply of renewable energy resources scattered in Japan, and the distance between their resources and municipalities, it will find the optimal matching between supply and demand for the whole of Japan.

The purpose of the research is to discuss the optimal power distribution to each municipality from renewable energy resources and the way of regional cooperation. The power grid is based on the National Grid and consists of 10 electric power companies, each of which is capable of power interchange, except for remote islands.

Linear programming is used for the optimization method, and scenarios are set based on the power generation potential of solar and wind power sources, their utilization rate, the transmission distance to the municipalities that consume electricity, and the electricity demand of the municipalities. The decision variable is the amount of electricity delivered from renewable energy located in municipalities to others that consume its energy on an annual basis.

Since there are 1,741 municipalities in Japan, the theoretical maximum number of combinations of power supply between municipalities is about 3 million.

The objective function is to minimize the sum of the power supply multiplied by the transmission distance. The reason for this is the cost of power delivery. Unlike conventional large-scale centralized power generation such as nuclear power generation and gas-fired power generation, the introduction of large amounts of distributed renewable energies will require the reinforcement and construction of new transmission lines and substations in various places.

To minimize the above-mentioned transmission line reinforcement and new construction costs, substation reinforcement costs, and transmission loss, it is required to produce and consume renewable energy locally and supply it to nearby demand areas as much as possible.

Constraints are set such that the renewable energy supply equals the municipality power demand and the upper limit of renewable energy supply is less than the installed capacity. Biomass and small hydropower are also renewable energy sources; however, only solar and wind power generations are considered in this study.

The optimization results show that 1,059 out of 1,741 local municipalities meet their power demands with renewable energy in their areas. The remaining municipalities, urban areas with higher demands, had to receive power from multiple other municipalities. For example, the cities of Osaka and Yokohama, which rank first and second in electricity demand, needed to receive electricity from 48 and 14 local municipalities, respectively, through cross-prefectural cooperation.

Environmental assessment of energy planning: the case of Spain 2015-2030

Monday, 3rd July - 17:30: Energy Systems 2 (B0.17 KOG)

Miquel Sierra [1]***, Joaquín Amenábar*** [1]***, Alexander de Tomás Pascual*** [1]***, Cristina Pérez-Sánchez*** [1]***, Cristina Madrid-López*** [2]

1. *LIVEN Lab, Sostenipra Group. Institute of Environmental Science and Technology (ICTA-UAB), Maria de Maeztu Unit (CEX2019-0940-M),* ***2.*** *Universitat Autònoma de Barcelona (UAB*

Long-term energy transition policies are often informed by optimization models, which are usually designed as black boxes and neglect environmental impacts other than carbon emissions and land use. This approach leads to incomplete data that hinders a comprehensive picture of the socio-environmental implications of such energy transitions. To fill this information gap, we created ENBIOS, an open-source python-based tool that integrates the detailed approach of life cycle assessment with a multi-scale metabolic analysis based on complex relations. The tool allows to analyze a broader range of indicators across hierarchical levels, from the entire energy system to the detail of individual energy production technologies.

Following European Union directives, the Spanish government has committed to the energy transition through the National Integrated Plan of Energy and Climate (PNIEC) 2021-2030. In this work, we analyze with ENBIOS the environmental impacts of PNIEC's 2030 energy production tendential and target scenarios and their changes with respect to the 2015 baseline. The focus of the analysis is set on the differentiation between foreground (installation and operation) and background (supply chain) impacts, which will allow us to regionalize results and assess, among others, the level of externalization of impacts. ENBIOS list of integrated indicators used in this work includes those derived from Life Cycle Impact Assessment (LCIA) ReCiPe methods and others currently being explicitly defined for this study.

Our preliminary results show a high degree of impacts associated with the production and installation of renewable infrastructure, which are partly foreground and partly background in the study. We then question the feasibility of these scenarios according to planetary boundaries and benchmarks of access to resources and limits of environmental impacts in Spain and other countries.

Decarbonisation of Corporate Electricity Procurement: Impact Assessment of the European Trade with Guarantees of Origin

Monday, 3rd July - 17:45: Energy Systems 2 (B0.17 KOG)

Aaron Paris [1], ***Ron-Hendrik Hechelmann*** [1], ***Nadja Buchenau*** [1]

1. *University of Kassel*

The growing social, economic and political importance of climate change has pressured more and more companies to develop decarbonisation strategies. One of the most common measures is the use of Renewable Energy Certificates (REC) to reduce emissions from electricity procurement (scope 2). A growing body of literature shows that REC, for example the European Guarantees of Origin, have a negligible effect on the installation of additional renewable energy capacity, if any, and neither displace fossil energy production nor support the energy transition.

Contributing to the existing literature, the trade with Guarantees of Origin is analysed to assess double counting of renewable electricity attributes as well as its consequences for corporate decarbonisation strategies. Subsequently, the potential consequences of the prohibition of national laws preventing double counting, as discussed for the upcoming revision of the European Union Renewable Energy Directive (RED III), are estimated. Building on existing studies, CDP data is used to quantify the gap between reported and actual emissions and estimate the impact of the current dominating greenhouse gas corporate accounting standard, the Greenhouse Gas Protocol. The results confirm the findings of existing literature and add evidence for the need to change corporate greenhouse gas accounting standards. Guarantees of Origin show no additionality effect and thus do not contribute to achieving climate mitigation goals. As scope 2 emissions make up for a large share of most company's greenhouse gas emissions, this must be considered when evaluating corporate reporting data to prevent erroneous conclusions.

Finally, alternatives to Renewable Energy Certificates for corporate decarbonisation strategies are discussed and recommendations for the announced revision of the Greenhouse Gas Protocol as well as the Renewable Energy Directive are given.

The novelty of this work is linking CDP data with the trade of Renewable Energy Certificates to assess the integrity of corporate decarbonisation strategies.

Food, agriculture, and biomass

Characterization and sustainability analysis of the redistribution of unsold meals from collective catering to associations: role of new operators

Monday, 3rd July - 16:30: Food, agriculture, and biomass (A0.51 KOG)

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In France as in many countries, circular economy principles are politically driven to foster societies' sustainable material use. Waste reduction receives particular attention in this field with food waste as a prominent field of policy action. As an example, the French EGalim Act voted in 2019 requires large establishments in collective catering to commit to a partnership for food donation from surplus meals to charity. This policy implies new steps and activities (packaging, collection, transport, storage, and distribution of donations) to be integrated into the supply chain. As a consequence, intermediary, new types of operators which handle these steps and activities for the account of donors and receivers have emerged. Taken together, they build a "new link" in the food supply chain. Because of its recent nature and relative complexity, very few studies have been carried out so far to understand how the collection and redistribution of unsold meals to associations work.

The NEWLINK project aims to characterize the "new link" of the redistribution of unsold meals from collective catering to associations and analyzes the role that different types of intermediary operators – companies and associations - play in dealing with unsold meals to be donated and what their contribution to more circular, less wasteful and sustainable food systems is.

We are developing a framework to analyze the new link using a multi-dimensional set of indicators. The study, which is in progress, is based on primary data collected along the new link – from large meal preparation units of public or private catering companies to intermediary operators to food aid associations — in the Paris metropolitan area (France). Data, obtained in in-depth interviews is qualitative and quantitative and covers various aspects related to business models, types of partnerships, quantities of collected and redistributed meals, and their composition. We suggest a typology of intermediary operators to understand their diversity.

The results will be analyzed by a twofold approach: i) an analysis of a multi-dimensional set of indicators of the newly implemented steps, between the catering sector and charity, according to the types of intermediary operators ii) a systemic analysis of their contribution to food waste reduction and the circular economy. Concluding remarks address the validity of surplus food donation to charity as a recent development fostering food system sustainability. Possible improvements will be synthesized as policy recommendations.

Dryland cropping: net-zero or resource efficiency?

Monday, 3rd July - 16:45: Food, agriculture, and biomass (A0.51 KOG)

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Australia is in the top-6 wheat exporting countries globally, with close to 75% of its production exported. Trends in global markets around greenhouse gas (GHG) mitigation and cleaner production are significant drivers for GHG reporting and mitigation. At the same time, agriculture sectors in Australia are developing GHG roadmaps with a view to contributing to a national "net zero 2050" target and are aiming to increase production (National Farmers' Federation, 2019).

Modelled scenarios for the Australian grain production show that reducing total emissions of the domestic sector could be in conflict with other objectives critical for sustainable agriculture such as resource efficiency and food security (Sevenster et al., 2022a). In the relatively low-input dryland environment that Australian grains are grown in, insufficient nitrogen (N) application is considered to be the largest cause of the gap between potential water-limited yield and actual yields achieved by farmers (Hochman et al., 2016; Hochman and Horan, 2018).

The Agricultural Production Systems Simulator (APSIM; Holzworth et al. 2014) was used to assess the GHG mitigation potential of nitrogen- and rotation management compared to reference scenarios developed for 2005 and 2015. The results showed that overall production could be increased by 50% or more when optimizing nitrogen management, without increasing net on-farm emissions. If nitrogen fertiliser could be supplied in such a way as to meet crop demand exactly, total fertiliser use was modelled to increase by a factor 3 compared to the 2005 reference. Nevertheless, net on-farm emissions would remain constant because extra emissions are balanced by increased carbon sequestration in soils. These effects could be further enhanced by selecting locally productive and low-emissions rotations. The increased use of fertiliser would lead to a considerable increase in embedded emissions, but the net GHG intensity of the system – including embedded emissions – would decrease by 20%.

The increased yields in the simulated scenarios are desirable, as the OECD-FAO Agricultural Outlook 2021-2030 (OECD/FAO 2021) forecasts a growth in demand for cereals and oilseeds of a little over 1% per year. This means that reduced production in Australia could lead to increased production and emissions elsewhere, either via indirect land use change or by shifting production to relatively higher emissions environment. Increasing production without additional land use or direct emissions aligns with objectives of resource efficiency and cleaner production. A considerable increase in yield would also potentially free up land to be used toward carbon sequestration via reforestation.

Similar results were found using data from a long-term field experiment conducted in Australian dryland cropping belt (Kirkby et al., 2016; Sevenster et al., 2022b) as well as a few other trials (e.g. Gan et al., 2014; Wang and Dalal, 2015). So-called nitrogen-mining in dryland cropping may lead to losses in soil carbon that can double GHG intensity of some grain production. Ignoring these effects of N-mining in GHG assessments or using ill-informed nitrogen-use-efficiency metrics could lead to perverse incentives.

The intrinsic link between carbon and nitrogen in soil organic matter and plant growth means that aiming to reduce absolute GHG emissions in dryland (water-limited) cropping systems toward "net zero" could be counterproductive. Instead, a focus on decreasing GHG intensity, of both the farm system and the production of fertilisers, while not increasing on-farm emissions or land use, can yield pathways that increase both resource efficiency and food security.

Towards a holistic carbon accounting framework for harvested wood products at sub-national level units

Monday, 3rd July - 17:00: Food, agriculture, and biomass (A0.51 KOG)

Oludunsin Tunrayo Arodudu [1], ***Obste Therasme*** [1], ***Timothy Volk*** [1]

1. *State University of New York, College of Environmental Sciences and Forestry*

Carbon stored in harvested wood products (HWP) can play an important role in climate change mitigation and needs to be accounted for accurately and consistently. This study reviewed the features of national HWP carbon accounting frameworks under the UNFCCC and Kyoto Protocol and recommended features suitable for reporting at sub-national levels. Recommendations for improvement of HWP carbon accounting framework at sub-national levels may include (i) evaluation of local or regional substitution effects of all produced and consumed HWPs, as well as their recycling and cascading use impacts (for improvement of previous assessments irrespective of the assessment tier level); (ii) local or regional measurements and estimations of half-lives, shelf life, lifetimes, obsolescence and fire incidence rates of different HWP classes in use and in solid waste disposal sites (SWDS), as well as their biogenic carbon values (for upgrade to tier 2 and tier 3 level assessments); (iii) derivation of local and regional decay functions (other than first order decay function recommended for tier 1 and tier 2 by the IPCC) for improvement of estimates of HWP carbon stock change (i.e., for upgrade to tier 3 assessments). Also important for the improvement of HWP carbon accounting framework at sub-national levels are (iv) improvements of the resolution of local or regional activity data (product category and process data) and conversion factors via collection and/or analysis of more detailed material flow information across all value chain involved i.e., within forests, sawmills and manufacturing plants, in-between forests and sawmills, sawmills and manufacturing plants, manufacturing plants and end consumers, end consumers and solid waste disposal sites, also from in-region to out-region and from out-region to in-region; (v) collection of exhaustive enterprise-level data on recycling and cascading use activities associated with HWPs for the purpose of capturing their full circular economy and climate change mitigation benefits (vi) engendering value chain modelling principles (which combines material flow information and life cycle assessment perspectives) to deal with unique and evolving reporting requirements e.g. estimation of substitution, recycling and cascading use impacts of HWP; and (vii) adopting a modified domestic origin-stock change approach to account for all HWP carbon stocks and flows relevant for climate change mitigation objectives at sub-national levels e.g. substitution effects, as well as recycling and cascading use impacts of retained, imported and exported HWP (depending on the availability of data). These recommendations will enhance the accuracy and/or precision of HWP accounting frameworks at sub-national level, help capture all potential benefits of HWP as a carbon sink for climate change mitigation, as well as a valuable contributor to other sub-national net zero emission targets.

Special Session: How Can Resource Classification Help Communicate the Future Availability of Raw Materials on the National level?

National resource classification: Opportunities and challenges

Tuesday, 4th July - 09:00: Special Session: How Can Resource Classification Help Communicate the Future Availability of Raw Materials on the National level? (B0.17 KOG)

Ulrich Kral [1]

1. *Environment Agency Austria*

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Dynamic Material Flow Analysis of Tantalum in the United States: a 19-Year (2002-2020) Perspective of Stocks and Flows

Tuesday, 4th July - 09:10: Special Session: How Can Resource Classification Help Communicate the Future Availability of Raw Materials on the National level? (B0.17 KOG)

Abraham J. Padilla [1], ***Nedal T. Nassar*** [1]

1. *U.S. Geological Survey*

Tantalum, a rare and very hard transition metal, has received considerable attention in recent years due to its increased use in advanced electronics and the high risks associated with its supply chain. In 2020, approximately 70% of the global supply of tantalum originated in Africa, with nearly 40% produced in the Democratic Republic of Congo alone where mining has been previously associated with human rights violations and armed conflict. In addition, several governments, including those of Australia, Canada, the European Union, the United Kingdom, and the United States, have designated tantalum a “critical mineral” (i.e., a mineral or element considered integral for the well-being of the economy, national security, and/or development of renewable energy and infrastructure). The United States, a leading consumer of tantalum materials, has been entirely reliant on imports to meet domestic demand for tantalum since the 1950s. However, properly quantifying total domestic tantalum consumption is problematic because two of the most important traded tantalum materials (Ta_2O_5 and K_2TaF_7) do not have unique tariff codes resulting in a significant portion of tantalum trade not being properly documented. Furthermore, once tantalum is incorporated into semi-finished and finished traded goods it is no longer tracked as tantalum. As a result, previous estimates only capture a fraction of total tantalum consumption in any given year.

In this study, we performed a dynamic material flow analysis using primarily international trade statistics for the United States to quantify total domestic tantalum consumption in all forms, including tantalum embedded in finished goods, and across the entire tantalum material life cycle (i.e., from primary production through post-consumer end-of-life [EoL]) between 2002 and 2020. Our results indicate that, on average, total domestic consumption was 103% higher, and some years as much as 257% higher, than previously estimated. Between 2002 and 2020, the United States consumed or *put into use* a cumulative 18,000 tons of tantalum metal (t-Ta). Consumption increased at an annual rate of ~5.8%, from an estimated 624 t-Ta in 2002 to 1,250 t-Ta in 2020. Electronic components, the leading global tantalum application, consistently accounted for a combined 40–65% of total domestic consumption, followed by aerospace and energy components (10–20%). Our results also indicate that the United States has become increasingly dependent on tantalum embedded in imported finished goods, which accounted for approximately 58% of all tantalum consumed domestically in 2020, compared to only 18% in 2002. As of yearend 2020, approximately 45% of all tantalum put into use since 2002 has been lost either during the primary processing and manufacturing stages or as disposals to landfills at the product EoL, including tantalum materials not recovered during the recycling process. Notably, we estimate that the United States consumed nearly half of all global primary tantalum produced between 2002 and 2020. This suggests that either a significant amount of global tantalum production is not accounted for, the amount of secondary (recycled) tantalum available is significantly underestimated, or both. Our detailed results also allow quantification of tantalum stocks in-use, by end-use application, as well as the quantity of tantalum coming out of use at the post-consumer EoL in any given year within the study timeframe, providing valuable insight to industry and policymakers for identifying possible above-ground tantalum resources that may be available for collection, recycling, and re-use as recovery technologies, especially for electronic waste, progress.

A practical approach for resource management using national level datasets for primary resources.

Tuesday, 4th July - 09:25: Special Session: How Can Resource Classification Help Communicate the Future Availability of Raw Materials on the National level? (B0.17 KOG)

Tom Bide [1]

1. *British Geological Survey*

The need to better understand how we source and consume the raw materials required for decarbonisation is driving a growing demand for data on mineral resources. A key application of these data is to understand resource potential, by evaluating known 'geological stocks' of raw materials based on estimates of mineral resources and reserves. However, the available resource data are often incomplete, totally lacking or compiled in different ways, making comparisons and aggregation near impossible.

A solution to these issues is the use of the United Nations Framework Classification (UNFC) to harmonise resource data for the. This has been done for a case study for UK which highlights the benefits of this approach for improving the understanding of resource issues. Simple decision-making tools are employed to assist with classifying existing resource data using UNFC. These are designed to be applicable to a wide range of datasets managed by national data providers. Their application to the UK, which has no system or national standard for collecting resource data, has served to highlight various issues relating to future mineral supply. These include the co- and by-product status of some minerals and the variations in approaches for different commodities.

The compilation of standardised datasets can benefit national resource management. For example, the results of this study provide a 'snapshot' of the state of the UK minerals industry and highlights where interventions may be needed if new projects to contribute to the green transition are to be developed. This exercise shows the benefits of standardised national resource inventories created using UNFC. However, it is also critical to treat each dataset and deposit individually as each has a unique combination of geological, social and environmental factors that determine if it can be developed. The use of the UNFC to classify mineral resource data facilitates inter-regional and international comparison and aggregations. It also supports the creation and adoption of evidence-based raw material strategies. However, it is important to understand the limitations related to data gaps, consistency of approach and harmonisation of datasets from diverse sources.

HOW CAN RESOURCE CLASSIFICATION HELP COMMUNICATE THE FUTURE AVAILABILITY OF RAW MATERIALS ON THE NATIONAL LEVEL?

Tuesday, 4th July - 09:40: Special Session: How Can Resource Classification Help Communicate the Future Availability of Raw Materials on the National level? (B0.17 KOG)

Soraya Heuss-Assbichler [1], ***Christoph Helbig*** [2], ***Ulrich Kral*** [3], ***Helmut Rechberger*** [4], ***Julia Stegemann*** [5], ***Patrick Wäger*** [6], ***Iman Dorri*** [1]

1. *Ludwigs-Maximilians-Universität München,* ***2.*** *Ecological Resource Technology, University of Bayreuth, Bayreuth, Germany,* ***3.*** *Environment Agency Austria,* ***4.*** *Vienna University of Technology,* ***5.*** *University College London,* ***6.*** *Empa-Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory*

There is a long tradition of assessing the availability of mineral resources based on geological, economic, and technological parameters. Reporting standards and codes developed are intended to attract investors. At the same time, sectoral or national classification systems are used to communicate the results of these assessments and based on this to monitor a country's reserves and resources.

Currently, the need for a consistent and transparent classification of all kind of resources is more than evident. It goes beyond the traditional mineral classifications, as sustainability aspects are decisively gaining in importance. Beside the level of confidence regarding the gained products and the technical feasibility of the project, its economic, environmental and social viability in the context of the legal aspects has to be considered. The United Nations Framework Classification for Resources (UNFC) meets these requirements, as it takes up one principle applicable to all types of resources.

Thus, the starting point of the discussion is to understand the meaning and principles of the resource as such. One of the advantages of the UNFC is that recycling or recovery projects can be classified in the same way as mining projects. However, the UNFC is usually applied at the individual project level and the approach for a national level has yet to be established. Two different approaches to communicating the future availability of secondary raw materials (SRM) at the regional or national level are discussed. One approach presented by Tom Bide is a bottom-up approach to estimating the resource potential of minerals by summarizing site-specific resource assessments in the UK. This approach is based on a decision tree. It has been applied by the French geological survey (BGRM) for secondary raw materials, e.g., mining residues and end of life magnets. Another approach presented by Abraham Padilla (USGS) reflects the application and benefits of Material Flow Analysis (MFA) for secondary resources, exemplified for the case of Tantalum.

As a result of the discussion, the information needed for a national resource classification is addressed and summarized. This includes challenges of a bottom-up approach to classify the recycling potential of secondary raw materials as well as the requirements for a top-down approach to classify the recycling potential on a regional or national level.

Special Session: The metabolism of Islands

A political-industrial ecology of houses and mining infrastructures in Svalbard

Tuesday, 4th July - 09:00: Special Session: The metabolism of Islands (A1.44 KOG)

Wendy Wuyts [1]

1. *Omtre AS*

This abstract is for consideration for the special session on **Metabolism of Islands.**

Islands are prone to multiple risks and infrastructural and spatial limitations for handling resources. However, islands can be seen as case studies for investigating the impacts of sustainability initiatives within well-defined boundaries. This presentation looks at circularity in Svalbard, a Norwegian archipelago.

Often transitions are investigated in an apolitical manner and without context which lead to outcomes that do not bring a lot of impact (Marin & De Meulder 2018). To assist circularity transitions, it is not only important to focus on one method, but a combination of methods from different fields to collect insights from different nature on a certain place (Marin & De Meulder 2018). One way of such interdisciplinary approach is applying political-industrial ecology methods that aim to investigate urban metabolism and foster circular metabolisms in a place (Newell and Cousins 2025; Wuyts et al. 2020). Applying it to an island context gives insights which practices and leverage interventions (do not) work.

Svalbard is a Norwegian archipelago which was first used as a base by the whalers in the 17th and 18th centuries, after which they were abandoned. Coal mining started at the beginning of the 20th century, and several permanent communities were established. The Norwegian Store Norske and the Russian Arktikugol remain the only mining companies in place. Currently, new building materials are imported over a long distance by boat, and the demolition waste is shipped back for incineration (LPO Arkitekter 2022).
However, we witness the emergence of the actualization of small practices of and discourse on circularity transitions in Svalbard:
The Sveagruva mine, the largest of the two mines of Store Norske, closed in 2017 and the land was given back to nature. In the meantime, records show that Longyearbyen is the fastest warming city in the world, made visible by avalanches and melting permafrost. This lead to the need for moving housing and infrastructures to less vulnerable locations (Interview, 2022). LPO Arkitekter, one of their main actors, did their first environmental and economic cost calculations and projects already, with actors like Vill Energi, Statsbygg and Store Norsk (Interview 2022). In 2021, they are part of the big Norwegian consortium Sirktre, led by Omtre AS. This study is done to take informed next decisions in 2023-2024.
The study is split up in a first part, applying industrial ecology methods and framework, and a second part, applying political ecology methods and frameworks.

Firstly, this study will shortly introduce the costs of 4 scenarios for one reference house in the Norwegian SirkTre project:

1. a business to usual case: linear one, including the GHG of the transport distances to incineration plants in Sweden
2. Deconstruct and reconstruct in Svalbard

3. Moving the house with a sledge
4. Radical one: Give it back to nature, let the houses be overgrown

Secondly, we share insights on the political, the systemic, structural challenges that hinder reuse of wood in an extreme island like Svalbard. With data from interviews, a field visit in Svalbard (2,5 weeks planned in February 2023) and historical data, this study provides a critical analysis of how Svalbard's linear metabolism of various housing and mining infrastructures came to be. These insights of both industrial and political ecology can assist speculations on how it can be transitioned ("back").

Tools for a regenerative and inclusive circular economy: Applications at a European and at an island level

Tuesday, 4th July - 09:15: Special Session: The metabolism of Islands (A1.44 KOG)

Filippos Zisopoulos [1], ***Daan Schraven*** [2], ***Martin de Jong*** [1]

***1.** Rotterdam School of Management, Erasmus University Rotterdam,* ***2.** Integral Design & Management, Delft University of Technology*

Regenerative economics offers a holistic framework to facilitate the transition towards a circular economy [1], [2]. But which tools (i.e., methods and indicators) can be used to study the complexity of human-made systems? And can these tools be applied at different levels of granularity? Here, we present two examples where we applied network-based quantitative tools to assess the regenerative potential of two different human-made systems. The first example takes a macro-level perspective on the material and energy flow metabolism of 27 EU Member States by using panel data from Eurostat [3], [4]. The second example zooms into the socio-economic metabolism of Samothraki, a Greek island in the north Aegean [5], [6] by using time-series data from socio-metabolic research [7]. Subsequently, we draw the most relevant insights, and we reflect on the challenges and limitations related to the application of these tools. Finally, we propose future research avenues which we think are important for developing further the upcoming scientific field of regenerative economics, and for contributing constructively to the transition towards a regenerative and inclusive circular economy.

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Socio-metabolic Risks and Tipping Points on Islands

Tuesday, 4th July - 09:30: Special Session: The metabolism of Islands (A1.44 KOG)

Simron Singh [1]

1. University of Waterloo

Submitted for the proposed special session: The Metabolism of Islands (proposers: Simron Singh, University of Waterloo, Canada; Bart van Hoof, University of the Andes, Colombia)

Small island states and jurisdictions are faced with significant sustainability challenges that stem from a variety of factors such as isolation from global markets, limited resource availability, heavy dependence on imports to meet basic needs, coastal development pressures, and reduced capacity for waste absorption. These challenges are further exacerbated by the negative impacts of global environmental change, such as global warming, extreme weather events, and pandemics, which can hinder progress towards sustainability. As such, small island economies are consistently ranked as highly vulnerable on various indices.

In this talk, I will introduce the concept of socio-metabolic risk (Singh et al. 2022), which refers to the systemic risk associated with the availability of critical resources, the integrity of material circulation, and the equitable distribution of derived products and societal services within a socio-ecological system. I will draw on socio-metabolic research conducted in several Caribbean Island states over the past few years to argue that specific configurations and combinations of material stocks and flows, and their "resistance to change," contribute to the proliferation of socio-metabolic risk (SMR) within these systems. These factors have a significant impact on the ability of the system to consistently and effectively deliver societal services necessary for human survival.

Governing SMR would involve governing socio-metabolic flows, and would require strategies to reconfigure the current system of resource-use in a way that is not only environmentally sustainable, but also socially equitable. Such interventions will be necessary to address the complex sustainability challenges faced by small island states and jurisdictions.

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Island circularity and Indigenous systems: the Hawaiian Ancestral Circular Economy and environmental justice in Hawaiʻi

Tuesday, 4th July - 09:45: Special Session: The metabolism of Islands (A1.44 KOG)

Kamanamaikalani Beamer [1], ***Kahiokala Elkington*** [1], ***Pua Souza*** [1], ***Axel Tuma*** [2], ***Andrea Thorenz*** [3], ***Sandra Köhler*** [4]

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In the face of the global climate crisis, there is an urgent need for alternative ecologically-based economic models. While the economic and environmental concerns of the Circular Economy (CE) are well-developed in CE literature, there remains a gap in research concerning CE's impact on culture and social equity. It is necessary to bridge natural and social science objectives in the CE, because the social and cultural pillars of the CE are under-developed, and the Universal Circular Economy Policy Goals call for a context and need-based framework.

Social development is essential to addressing climate change and it is critical to include social sciences in global environmental research (World Bank, 2021). In this paper, we examine how in Hawaiʻi, the Hawaiian Ancestral Circular Economy (ACE) and contemporary Indigenous-led community approaches toward advancing economic justice can be a model system for understanding principles of circularity because of aloha ʻāina, a framework for reciprocal care of human-environment relations. This work achieves the necessary interdisciplinary collaboration required to address global environmental challenges by bridging non-Western and Western, social and technical approaches to sustainability studies.

Inspired by shared commitments to sustainability and a common goal of achieving sustainable and equitable societies, this paper represents an international, multidisciplinary collaboration that seeks to produce emancipatory research. We put into conversation differing worldviews, areas of expertise, and tools of inquiry to present a discussion of why islands and indigenous systems are important models to study the CE and sustainability. This is achieved through literature reviews on the potential of islands as model systems for studying the CE, and key components of the Ancestral Circular Economy in Hawaiʻi. We then delineate how Indigenous knowledge has the potential to inform the redesign of global economic processes toward sustainability, and introduce how community responses to crucial issues in Hawaiʻi demonstrates that socio-economic embeddedness is necessary to achieve the goals of a CE. This builds off of previous work where CE's engagement with indigenous knowledge systems is proven to be an opportunity to ally and produce solutions to the challenges associated with changing the linear economy through the analysis of case studies from Hawaiʻi and Germany (Beamer et al, 2021).

Hawaiʻi upholds principles of an indigenous economy that supported a thriving economic infrastructure, promoted ecological health, and sustained a substantial population prior to American imperialism. Today, the islands are situated at a midpoint of the global economy, and are extremely import-dependent and linear. Hawaiʻi is a model system to study the CE since the scale of islands theoretically makes it simpler for political or economic sectors to collaborate in achieving sustainability at a manageable scale. As a result of a partnership between technical and social science approaches, the findings in this paper present how indigenous knowledge has exceptional potential in informing the transition to sustainability – especially in addressing important social equity gaps and concerns of community stakeholders. By determining components of Indigenous sociocultural systems, this paper introduces the concept of the Ancestral Circular Economy, and we present how aspects of this Indigenous institution can develop the social and cultural pillars of the CE and inform the development of the Universal Circular Economy Policy Goals.

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Interdisciplinary island metabolism: intersection of flows and socio-geography approaches to investigate vulnerability, waste colonialism and externalization in the cases of Comoros and New Caledonia.

Tuesday, 4th July - 10:00: Special Session: The metabolism of Islands (A1.44 KOG)

Jean-Baptiste Bahers [1]

1. CNRS, UMR ESO, Université de Nantes

Islands are closely linked to globalized material flows, with specific constraints and vulnerabilities. Counter-intuitively, they are not examples of metabolic loops of consumption, production and waste. We argue that islands are key territories for better understanding the consequences of flow in terms of vulnerabilities, colonialism and externalization, precisely because of the way they are connected (rather than isolated) to globalized material flows.

This research is an interdisciplinary material and geographical analysis of waste realities in two French/formerly French island territories (Manglou et al., 2022; Bahers et al., 2022): the Comoros and New Caledonia. It draws on metabolic analysis and waste studies to address the different perspectives that these approaches open up for the study of island territories. An analysis of material flows (EW-MFA method with a spatialization of flows) allows us to sketch out metabolic profiles that show the contribution of the dominant mining and agricultural industries to waste production. This flow approach is combined with a social geography approach. The socio-political context of each island is used to explain contemporary resource and waste management policies and practices.

The comparison of current situations in terms of discourse and flow economics shows how these territories are characterized by the accumulation of waste, which characterizes a colonialism of waste (Lepawsky, 2015: Liboiron, 2018, 2021). This is not the export of waste from rich countries to poorer ones, but the export of resources extracted from poor countries to rich ones while keeping the extraction waste there. This is the case with nickel waste in Caledonia and oil waste from ylang ylang extraction in the Comoros. This externalization of resources and their circulation thus provokes island vulnerabilities.

In conclusion, there is a need for interdisciplinary research (Bahers et al., 2022) into island metabolism in order to understand the link between the circulation of flows and their socio-geographic consequences. This framework, which combines a territorial ecology and a political ecology of the islands, makes it possible to grasp the intersections between extractive economic sectors and sociometabolic vulnerabilities.

Réferences

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Sustainable Textiles and Circularizing Organic Waste of Grenada (SIDS)

Tuesday, 4th July - 10:15: Special Session: The metabolism of Islands (A1.44 KOG)

Shannon Henry [1]

1. *The Kaylia Group*

The fashion and textile industry contributes about 1.2 billion tons of greenhouse gas (GHG) emissions annually. The production and degradation of synthetic fibers derived from petroleum constitute a significant portion of these emissions, highlighting the need for the development of more innovative and sustainable textiles. This talk proposes a dialogue on industrial symbiosis (IS) opportunities for small island developing states (SIDS), starting with Grenada. The goal is to promote research for uncovering IS relationships between agricultural industries of SIDS and the global textile production industry. To do this, we must discuss possible resource exchanges and conduct life cycle assessment (LCA) into the viability of fibers extracted from organic waste of SIDS, creating a bridge between SIDS and the global textile industry.

We will discuss how an industrial symbiosis approach would enhance the decarbonization of the textile value chain through the utilization of organic waste, serving economic, social, and environmental interests of SIDS and its policymakers. Major fiber development companies like Lenzing (Austria), Advansa (Germany), and organizations like the European Commission are dedicated to developing alternative fibers and closed loop production methods for a more circular economy. Textiles derived from the hemp plant and orange fruit extract, for example, have been studied to emit 30-50% less total carbon emissions compared to cotton and polyester. Further, plants with high hemicellulose (HEM) and cellulose (CEL) content requiring little agrochemicals for growth are excellent alternatives to high carbon footprint natural and synthetic fibers.

Why Grenada? Grenada exhibits abundantly available agriculture with very little use. This talk will discuss the possibility of a study to determine the following: (1) the fiber yield of a number of Grenada's abundant agriculture (2) clarify fiber composition and determine industrial applications of the fibers (3) determine which extraction methods are economically and temporally feasible for the island's farmers (4) innovate on LCA methods to promote effective exchange of resources among the involved industries. Grenada's island system makes it an ideal subject for this research: it is data poor, rich in plant biomass, and has a low resource throughput. The problem of pollutant textiles is a global one, and Grenada is not a producer of carbon emissions related to textiles, however, the island is most vulnerable to the effects of climate change that result from industrial GHG emissions. Circularizing the waste of Grenada's agricultural system to feed the global textile industry would help to develop a model for IS to be replicated by neighboring SIDS. Ultimately, the goal of uncovering IS opportunities connected to SIDS islands is to lessen the impact of global GHG emissions on vulnerable populations, long term.

This talk will introduce preliminary data around Grenada's agricultural network and LCA of the island's abundant crops to determine which category of organic waste would produce the most effective, and high quality fibers, with the lowest possible environmental impact. Current data suggests that Grenada sits on a gold mine of organic waste with the potential to develop value-added products that will improve its import/export ratio. In 2020 Grenada's import/export ratio was USD 383 million (import) to USD 24.7 million (export). Uncovering IS opportunities for Grenada would: circularize its organic waste, increase its export ability for economic growth, disseminate knowledge around sustainability, and enhance the overall well-being and social metabolism of the island.

Ex-ante LCA 2

Life-cycle Assessment Integration into Scalable Open-source Numerical models (LiAISON) for analyzing emerging low-carbon technologies

Tuesday, 4th July - 09:00: Ex-ante LCA 2 (C0.06 KOG)

Tapajyoti Ghosh [1], ***Patrick Lamers*** [1], ***Shubhankar Upasani*** [1], ***Romain Sacchi*** [2], ***Vassilis Daioglou*** [3]

1. National Renewable Energy Laboratory, 2. Paul Scherrer Institute, 3. PBL Netherlands Environmental Assessment Agency,

Decarbonizing the industrial sector is a significant challenge in achieving a net-zero greenhouse gas (GHG) emissions economy by 2050 and the Paris Agreement, i.e., a global climate change mitigation target of achieving a maximum average temperature change potential of 1.5°C or less by 2100 with respect to pre-industrial levels. In the United States (US), the industrial sector accounts for 23% of total GHG emissions and is home to a number of hard-to-electrify activities. The chemicals subsector has the single largest subsector emissions profile after direct emissions from fossil fuel combustion and leakage from fossil fuel distribution systems. Within the chemicals subsector, many processes depend on hydrogen or ammonia precursors. Decarbonizing these two commodities would contribute significantly to decarbonizing the industrial sector as hydrogen could also be used for low carbon steel production (e.g., hydrogen-based direct reduction of iron) and other industrial applications.

Emerging technologies require the application of prospective life cycle assessment (LCA), which can account for technology (foreground) scaling and process improvements via learning-by-doing, among others. In many cases, the future system context (background) in which the technologies are assumed to operate in is equally relevant. Background scenarios generated by integrated assessment models (IAM) can coherently incorporate potential future dynamics of the energy-climate-human-land system. Further, IAM scenarios are harmonized across socioeconomic and climate change mitigation pathways, which facilitates the comparability of prospective LCAs using different IAMs.

We introduce an open source prospective LCA framework, the Life-cycle Assessment Integration into Scalable Open-source Numerical models (LiAISON), to analyze the non-linear relationships between technology foreground and the future energy system background across a series of midpoint and resource use metrics The integration of LCA and IAM data is achieved using prospective environmental Impact assessment (PREMISE). We showcase it by assessing two Power-to-Hydrogen (PtH2) processes, namely Solid Oxide Electrolysis (SOE) and Polymer Electrolyte Membrane Electrolysis (PEME). We compare the technologies to a baseline of hydrogen production via natural gas-based Steam Methane Reforming (SMR) in a US context of multiple energy system and climate change mitigation futures. Besides providing an analysis that specifies the LCA results ranges with temporal and geospatial explicitness across the two technologies, metrics, and impact assessment methods, this research also aims to establish a base framework that can be expanded to use other IAM generated scenarios and US open-source life cycle inventory (LCI) databases. We find that the temporal environmental performance of either technology or their difference to SMR is directly influenced by the underlying background dynamics. Under baseline projections (i.e., no decarbonization goals), neither process reaches parity with the incumbent technology across several environmental metrics. Under the decarbonization scenarios, the underlying sectoral shifts result in declining impacts over time, compared to 2020 levels, except for metal depletion levels, which increase. The background shifts postulate a heavily decarbonized economy and energy system, which help technologies reach parity with SMR between 2040-2050 (RCP2.6) and 2030-2040 (RCP1.9) for global warming. Despite declines across several other metrics over time, neither PtH2 technology break even with SMR by 2100 besides for global warming.

Future environmental impacts of passenger vehicles

Tuesday, 4th July - 09:15: Ex-ante LCA 2 (C0.06 KOG)

JORIS ŠIMAITIS [1], ***Stephen Allen*** [1], ***Rick Lupton*** [1], ***Christopher Vagg*** [1], ***Isabela Butnar*** [2]

1. *University of Bath,* ***2.*** *University College London*

Road transport contributes 11.9% to global greenhouse gas emissions (GHGs) with the leading decarbonization strategy replacing fossil-fuelled combustion vehicles with electric vehicles. Most life cycle assessment (LCA) studies confirm that electric vehicles have lower GHGs compared to combustion vehicles although can increase impacts in other categories such as resource depletion and toxicity. However, impacts are calculated as if they happen today using current data which while representative of the production phase, is not representative of the use phase which extends years into the future before the vehicle reaches end-of-life. Use and end-of-life impacts depend on future progressive changes in impacts of fuels, electricity, and other processes which are not considered in typical LCA. In response, this work conducts a time-adjusted prospective LCA (pLCA) to investigate the environmental impacts of current and future passenger vehicles considering global decarbonization scenarios. Base and RCP1.9 scenarios from an integrated assessment model – IMAGE – in ‘premise’ were used to prospectively transform multi-sector activities in ecoinvent v3.8 and conduct a time-adjusted prospective LCA (pLCA) in Brightway2 using passenger vehicle inventories from carculator. Our results show that when future scenarios are considered for vehicles produced today, in most cases the impacts of vehicles are up to 45% lower than expected (GHGs, air pollution, toxicity). While electric vehicle offers lower life-cycle GHGs in most cases, it is at a compromise of greater impacts in most other categories. Furthermore, the ‘choice’ of the vehicle can vary substantially between the major regions and adoption year of the vehicles. The outcome of this research aims to provide a better representation of passenger vehicle sustainability and offer methodology advancements in the LCA of long-lived products.

Learning curves: using historic trends in forecasting and backcasting environmental footprints

Tuesday, 4th July - 09:30: Ex-ante LCA 2 (C0.06 KOG)

Mitchell van der Hulst [1], ***Mark Huijbregts*** [1], ***Rosalie van Zelm*** [1], ***Mara Hauck*** [2]

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The economic and environmental costs of existing and emerging technologies have been found to decrease over time as a result of a phenomenon categorized as "learning". Learning curves describe the log-linear correlation between the amount of learning that has occurred and some learning dependent parameter, such as a product's cost or environmental impact. This learning can be the result of many mechanisms, such as learning-by-doing (experience from production), learning-by-searching (R&D), and learning-by-exchanging (intra- and interorganizational knowledge transfer), to name a few. In its simplest form, a learning curve lumps these mechanism together into a single learning parameter, which can be approximated by parameters such as cumulative production. The formula for the learning curve is a simple power law, where the exponent is indicative of the rate of learning. The higher the learning rate, the faster the dependent parameter, e.g. cost per unit output decreases as a result of learning mechanisms. More advanced approaches disentangle the various contributing learning mechanisms into distinct learning rates.

The learning curve concept has mostly been applied in economics to explain cost reductions as a result of increased knowledge about the product through learning. Economic learning curves have been successfully used to both explain historic and predict future trends in cost. Furthermore, one could use learning curves both to forecast future costs assuming learning increases at an equal rate, or to backcast the amount of learning that needs to occur for a certain desirable cost to be reached. It should be noted that these learning curves are based on empirical evidence and that no mechanistic or causal correlation has been found that can further explain this log-linear learning behavior.

In recent years, it has been hypothesized that the learning curve concept can be applied outside of economics in fields such as environmental science. Several studies indicate that environmentally relevant parameters such as process energy intensity or carbon footprint do behave like learning dependent parameters that follow the simple power law behavior of a learning curve. For example, in prospective life cycle assessment (LCA), learning curves have been proposed as a tool for projecting future environmental impacts of emerging technologies, for which LCA relevant data is typically scarce. However, the availability of environmental learning curves is currently too limited to validate whether the power law relation holds for a broad range of products. Furthermore, data to derive environmental learning curves is also scarce. This data scarcity hampers broad application in prospective LCA or other disciplines of environmental science.

In our work, we describe, demonstrate, and compare methods to derive environmental learning curves for various products, highlighting the pros and cons of each approach. One of these approaches is a component-based bottom-up approach in which individual learning rates of components in emerging technologies are determined by collecting empirical evidence for existing production of these components. These can then be combined to create a dynamic life cycle inventory, which is used to calculate footprints at various points in time. From these calculated results, the environmental learning curve of the emerging technology can be derived for use in prospective LCA. This approach is demonstrated with an example case study.

Understanding the performance of a novel technology to produce hexanoic acid from CO2 and renewable electricity

Tuesday, 4th July - 09:45: Ex-ante LCA 2 (C0.06 KOG)

Jisiwei Luo [1], ***Mar Perez-Fortes*** [1], ***Adrie Straathof*** [1], ***Andrea Ramirez*** [2]

1. Delft University of Technology, 2. Technical University Delft

In the context of fostering energy transitions to reduce carbon emissions in the chemical industry, new technologies combining CO_2 electroreduction and renewable energy usage (e.g. solar, wind) are emerging. Among those, microbial electrosynthesis (MES) is gaining attention as it allows the production of high-value-added products from CO_2. An interesting product from this route is hexanoic acid, which has a growing market demand and high market value. Hexanoic acid is currently a by-product of palm kernel or coconut oil production. This route is, however, concerning. Its production level is strongly dependent on finite natural resources such as land. Consequently, its sustainability is questioned, given the increasing demand for hexanoic acid. Featuring the potential to reduce CO_2 emissions, high market value and demand, and savings on natural resources, producing hexanoic acid using a combination of MES and renewable energy is attractive. However, in contrast to traditional constant power supplied to chemical processes, renewable energy fluctuates in nature. Therefore, this newly introduced technical challenge will impact the design of systems and the associated costs.

In this study, we evaluate the impact of using intermittent energy sources in the design and performance of a MES plant that produces hexanoic acid at an industrial scale. This ex-ante technology assessment combines conceptual plant design with economic and environmental analyses. We assess the performance of a plant producing 10 kt of hexanoic acid at 99% purity under three scenarios: 1) the plant is operated continuously (base case); 2) the plant follows the load of a hybrid renewable power park (i.e. solar plus wind), and 3) energy storage in the form of storage tanks are included in the design to minimise the impact of intermittency. Note that in electrochemical concepts, electricity acts as a main feedstock to the plant, and therefore, any variability will directly affect the amount of product that can be produced from the reactor.

The plant was designed by practising conceptual process design in Aspen Plus. Moreover, the operation (i.e. scheduling) and sizing of the storage tasks under intermittency were optimised via linear optimization. Our results indicate that if the load of the hybrid renewable park was followed, the plant would need to shut down for about 2678 hours due to technical constraints (e.g., in the downstream processing). This results in a 31% increase in the levelised cost of the product compared to 3.6 k€/tonne in the base case. Deploying the storage tanks could reduce the shutdown time to around 1152 hours and decrease the costs to 4.4 k€/tonne, which is still 22% higher than the base case. We are currently conducting a life cycle assessment to understand the environmental trade-offs of the different cases. The results of the ex-ante assessment will allow us to 1) identify hotspots regarding the implementation of novel concepts in renewable-based energy systems (e.g. solar, wind) and 2) gain insights into the design and ex-ante modelling of novel electrochemical technologies.

Evaluating the impact of background system on carbon capture and utilization (CCU) pathways in Canada from 2020-2050

Tuesday, 4th July - 10:00: Ex-ante LCA 2 (C0.06 KOG)

Mengqing Kan **[1]*****, Sylvia Sleep*** **[2]*****, Heather L. MacLean*** **[3]*****, I. Daniel Posen*** **[3]**

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Carbon capture and utilization (CCU) is considered as a potential strategy to reduce greenhouse gas (GHG) emissions in the production of chemicals and fuels. Despite widely differing processes and reactions, most CCU pathways need similar inputs, such as electricity, hydrogen, and heat, which are the common background system factors. The GHG intensities of these process inputs are critical drivers of the life cycle GHG emissions of different CCU pathways, and therefore strongly influence the decision regarding which (if any) CCU pathways to prioritize for continued development or eventual deployment. The goal of this study is to evaluate the impact of background systems on CCU pathways to produce chemicals and fuels, and to identify how different pathways perform under a set of harmonized dynamic projections for the background systems. Using the Canadian energy system as a case study, we model the cradle-to-gate GHG emissions from 26 CCU chemicals and fuels (e.g., methanol, formic acid, ethanol, and carbon monoxide) from 2020 to 2050 for 12 different scenarios encompassing different technological readiness levels (TRLs) of CCU pathways and emission factors of key background systems over time. For each CCU pathway, we identify a benchmark conventional product, and analyze both under equivalent background scenario projections to assess under what conditions the CCU route can achieve lower GHG emissions than its conventional counterpart. The results show that GHG emissions for most pathways vary greatly based on the background system, with electricity intensity being the most impactful factor. To minimize GHG emissions, a low carbon electricity intensity is crucial, but having low electricity intensity does not guarantee lower emissions compared to conventional pathways. The choice of buying bulk hydrogen or producing it onsite, the market penetration of water electrolysis technologies, and the use of electric boilers also play a significant role in reducing GHG emissions in industrial plants. The study also highlights the need to take into account the technological maturity of different pathways when identifying the most promising ones, and assessing their potential to assist with near-to-medium term GHG mitigation efforts. The next step in the research will be to evaluate the use of carbon capture and storage (CCS) technology for the benchmark conventional route of each chemical analyzed. This will help identify the circumstances where the CCU route can result in lower greenhouse gas emissions compared to the conventional route, considering the availability of a greener option for the latter.

A life-cycle perspective on the benefits of renewable electricity generation in the EU27

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 10:15: Ex-ante LCA 2 (C0.06 KOG)

Evert Bouman [1]***, Francis Barre*** [1]***, Gaylord Booto*** [1]***, Babak Ebrahimi*** [1]

1. *Climate and Environmental Research Institute NILU*

Introduction

The generation of electricity and heat contributes significantly to annual anthropogenic greenhouse gas (GHG) emissions of the European Union (EU). Despite multiple demonstrated benefits for human health and the environment associated with the reduction in fossil fuel use for energy, the increased use of renewable energy sources (RES) is not impact free and may come at a cost to the environment. Here, we present the benefits and trade-offs of the use of RES for the production of electricity for the Member States of the EU27 from a life-cycle perspective.

Approach

We construct a parametric life-cycle model of electricity generation accounting based on a collection of life cycle inventories (LCIs) describing archetypical electricity generation processes for a total of sixteen different renewable and non-renewable energy sources. Using available national statistical data on fuel consumption, fuel characteristics, and gross electricity production, sourced from Eurostat, these LCIs are adapted to create inventories specific to (renewable) energy source, year, and Member State. These specific LCIs are then used to calculate potential environmental impact intensities for electricity generation, distinguishable by energy source and Member State, and for any given year in the period 2005-2020. Based on an energy system scenario specific to the EU27, we additionally calculate life-cycle impacts in the period 2020-2050 at the same resolution.

Main results

Life cycle impact intensities for electricity production are found to differ considerably across energy conversion and between Member States and years, driven by differences in fuel conversion efficiency and capacity utilization. Impact intensities (i.e. impact indicator per unit electricity produced) are driven by a wide range of processes and emissions to the environment, but opportunities exist to decrease impact intensities for singular processes, either by focusing efforts to increase efficiency, or to implement emission mitigation technology. The increased use of RES has led to an absolute decrease in life-cycle impact indicators in the period 2005-2020 for most impact indicators investigated in this study. Annual gross electricity production has remained relatively constant in this period. This decrease is mainly driven by the increased production of onshore wind power and solar photovoltaic power relative to 2005, followed by electricity production from sources such as biogas and solid biomass, and the corresponding reduction in fossil fuel generated electricity. These effects continue to be apparent in a forward-looking scenario post 2020.

The increased use of RES comes at a cost in terms of freshwater ecotoxic impacts (e.g. related to the solar PV value chain) and land occupation impacts (related to the production of solid biomass). These costs are partially compensated for by using a mix of renewable sources to produce electricity, thus dampening the effects of problem-shifting caused in the value chain of singular renewable sources. Diversification of the electricity supply across various types of renewable energy sources is therefore recommended compared to full-scale investment in a single renewable electricity source. Lifetime extension is an option to further mitigate negative consequences from the increased use of non-combustion RES, as impact intensities decrease due to increased infrastructure longevity.

Funding information

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LCA methods 1

Influence of Irrelevant Alternatives on Choices with Environmental Attributes

Tuesday, 4th July - 09:00: LCA methods 1 (A0.51 KOG)

***Mirel Yavuz* [1], *Guia Bianchi* [2], *Charles Corbett* [1], *Tayler Bergstrom* [1], *Aimee Drolet* [1], *Timothy Malloy* [3], *Deepak Rajagopal* [4], *Rakesh Sarin* [1], *Francesco Testa* [5]**

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With the advent of life-cycle assessment (LCA) and related methods, decision-makers have increasingly good information available about the environmental consequences of their choices. Those methods tend to implicitly assume that decision-makers are rational when making trade-offs between environmental attributes. Less well known is how existing biases documented in behavioral science influence their choices. We show that decision-makers are equally vulnerable to context effects when facing choices involving trade-offs between environmental attributes as they are with conventional attributes. When analysts present the environmental impacts of various alternatives to policymakers or other decision-makers, seemingly innocuous choices in how to present that information can have a major effect on which alternative is chosen. We examine two context effects, the attraction and compromise effects, in which the choice between two alternatives may be influenced by a third alternative even when the latter should be irrelevant. We replicate an earlier study on choices involving non-environmental attributes and conduct an equivalent set of experiments involving trade-offs between environmental attributes. We show that context effects are frequently significant and substantial in the non-environmental as well as environmental settings; the choice frequency can change by 30 percentage points after adding an irrelevant alternative. Our results highlight the importance of incorporating behavioral science into the broader environmental literature that involves trade-offs between environmental attributes, beyond its already established role in behavioral environmental economics.

Towards Intelligent Life Cycle Assessment: Solutions and Potentials of Large Language Models

Tuesday, 4th July - 09:15: LCA methods 1 (A0.51 KOG)

Jianchuan Qi [1], ***Nan Li*** [1], ***Jing Guo*** [1], ***Ming Xu*** [1]

1. School of environment, Tsinghua University

The advent of Large Language Models (LLMs) like ChatGPT heralds a new phase of Artificial Intelligence (AI) evolution, pushing the frontier of possibilities to new heights. However, the application of LLMs in specialized domains sparks controversy, primarily due to the lack of domain-specific knowledge and the risks of data hallucination.

Responding to this challenge, we present a solution to enhance the applicability of LLMs, focusing particularly on the field of environment, ecology, and sustainability. In particular, we explore the profound potential of LLMs in the domain of Life Cycle Assessment (LCA), a field where LLMs' data processing capabilities, pattern recognition, and natural language understanding can significantly enhance analytical efficiency, result precision, and user experience.

First, our study positions LLMs as an innovative tool to parse, integrate, and comprehend complex and scattered LCA data. The inference capabilities of LLMs enable them to identify relationships and uncover hidden patterns within the data. This function facilitates a comprehensive and precise evaluation of the environmental impacts associated with the life cycle of products and services.

Second, LLMs significantly enhance user interactions by creating a natural language understanding and response mechanism. This feature promises a more intuitive and user-friendly interface for practitioners in the field, accelerating the processes of querying, analyzing, and making informed decisions in the LCA framework.

Third, the intelligent task-performing capabilities of LLMs, such as identifying flows or recommending greener unit processes, signal a critical progression in the design, production, and adoption of sustainable products and services. Such a development can further contribute to a paradigm shift in environmental and sustainability sciences.

We argue that the strategic incorporation of LLMs into LCA could instigate a profound shift in the traditional paradigm, transforming the practice into a more intelligent, efficient, and user-friendly system. Our presentation will elucidate the prospects of LLMs in LCA, offering novel insights and potential solutions for their successful application in environmental and industrial ecology.

Characterizing impacts of macroplastic debris on marine biodiversity

Tuesday, 4th July - 09:30: LCA methods 1 (A0.51 KOG)

Marthe Alnes Høiberg [1], ***Francesca Verones*** [2], ***Konstantin Stadler*** [2]

1. *Norwegian Univ. of Science and Technology,* ***2.*** *NTNU*

Plastic pollution is widely acknowledged by scientists, policy makers and the public alike as a pressing environmental issue. Detrimental impacts of entanglement and ingestion of plastic items have been documented for marine animals from across the globe for decades already. Yet, conventional sustainability assessment methods such as Life Cycle Assessment (LCA) fail to account for the probability of mismanagement and subsequent negative impacts of the plastic items once astray in the natural environment. This leaves one of today's biggest environmental concerns out of the equation of environmental impacts associated with plastic products. However, the nature of plastic pollution differs from more traditional stressors included in LCA, as emissions of plastic are by default unintended events that may or may not occur, as opposed to point emissions of compounds that can be measured for a given industrial process. Moreover, plastic products as debris remains particularly challenging for modelers to tackle owing to the innumerable combinations of polymer types, shapes, and sizes, which again are subject to change once in the marine environment due to weathering processes. These properties influence both the fate and potential effects of plastic debris, and different impacts are relevant to consider depending on e.g., the size of the item in relation to the size of an organism. This complexity and inherent uncertainty is not easily reduced to categories that are meaningful, while at the same time applicable for LCA practitioners. As the primary step, impacts of mismanaged plastic are usually split into those arising from microplastic (<5 mm) and macroplastic (>5 mm). Here, we present an approach for characterizing the impact of entanglement in macroplastic for marine species globally. This is achieved by combining a Species Sensitivity Distribution (SSD) effect model with the fate of buoyant macroplastic on the ocean surface, estimated using Lagrangian particle tracking. As the majority of the material found to cause entanglement hazard to marine animals appear to stem from the fishing industry, the individual trajectories of the fate model were defined by using fishing hotspots within each country's exclusive economic zone (EEZ) as release point locations for the modelled plastic particles. We discuss how different country-specific release locations potentially influence the impact on marine biodiversity and identify further research needs in order to achieve a spatially explicit impact model for marine macroplastic debris originating from both land- and sea based sources.

Coupling Mobility Model and Life Cycle Assessment to Ecodesign Neighbourhood Project

Tuesday, 4th July - 09:45: LCA methods 1 (A0.51 KOG)

Cyrille Francois [1]***, Nicolas Coulombel*** [2]

1. *Université Gustave-Eiffel,* ***2.*** *Laboratoire Ville Mobilité Transport - Ponts ParisTech*

As cities extend and renew, neighbourhood projects need environmental assessment methods in order to limit the pressures of urban areas on the environment. Significant research has been conducted on building modelling and Life Cycle Assessment (LCA). Transportation is a major source of impacts and therefore also requires in-depth investigation, especially in regard of interactions that occur between mobility and the built environment.

This presentation aims to develop an environmental assessment methodology that considers life cycle effects related to mobility and the transportation system in the case of an urban neighbourhood. In addition to analysing urban transport technologies through a LCA, our methodology puts emphasis on the representation of mobility using microsimulation in order to better consider neighbourhood characteristics. Based on a literature survey that reviews the various methods to represent and evaluate mobility at the local level, our methodology builds on a disaggregated or agent-based approach, as proposed by Anderson et al. 2015 or Saner et al. 2013, while keeping LCA completeness and transparency. A case study on a future neighbourhood close to Paris will illustrate our methodology and reveals the leverage of both urban planning and location choices.

To represent daily mobility associated to future neighbourhoods, we develop a stochastic modelling chain, starting from neighbourhood characteristics, with dwellings and jobs, then sequentially the description of potential population, daily mobility and transport system usage. The environmental impacts of transport modes are then assessed through a LCA, including exhaust emissions, fuel production, vehicle production, maintenance and end-of-life, and finally infrastructure, both for private cars and public transit.

Using our assessment framework, we estimate daily mobility patterns and related environmental impacts for an actual neighbourhood project. Results highlight various policy instruments that influence the environmental burden. In addition to sensitivity related to transport technological choice and efficiency, we point out effects related to neighbourhood definition, in the hand of building promoters and urban planners. Besides location and urban form, dwelling size, car park availability and public transport pass incentive measures also have significant impacts on the environmental footprint of daily mobility. To conclude, a parallel study is carried out for the same neighbourhood on buildings. It emphasizes the significant role of transportation regarding the environmental impacts of urban projects, with global warming impacts almost equivalent between buildings and transportation.

Mind the incertitude: a call for mainstream adoption of global sensitivity analysis and Bayesian approaches in LCA

Tuesday, 4th July - 10:00: LCA methods 1 (A0.51 KOG)

Carlos Felipe Blanco [1], ***Stefano Cucurachi*** [1]

1. *Institute of Environmental Sciences (CML) - Universiteit Leiden*

"We live in times of great uncertainty" is what we all heard our elders repeat, only to be confronted years later by an even more turbulent period that justified our taking over the phrase. Yet, an extensive body of literature (see e.g. Scoones & Stirling 2020) that evolved considerably over the past decade found the concept of ***uncertainty*** to be inadequate to capture the full depth and broadness of what keeps us awake at night. We need a new set of definitions to hit the curveballs the beginning of the millennium has thrown at us: pandemics, war, climate change, insect decline, and the era of post-truth, to name some. Stirling proposed the term ***incertitude*** instead. Such reframing is highly relevant to the new generations of LCA practitioners who with youthful vision and vigour will jump to label, analyse and propagate what the LCA world commonly refers to as *uncertainty*. Instead, Stirling labels this "uncertainty" as ***risk***. Following Stirling's conceptualization, the "risk" box is only a comfortable place for highly unrealistic situations where we have good knowledge of possible outcomes and can quantify each outcome's likelihood. This is typically not the case in most LCA models.

And so, we LCA modellers and practitioners have been incorporating poorly measured variabilities, assumed and/or subjective uncertainties and uncertainty based on semiquantitative data quality ("pedigree") estimates in the blender of uncertainty propagation via Monte Carlo. We serve the results as a tropical juice with the enchanting aroma of scientific robustness that impressive-looking probability distribution curves or boxplots give. To avoid any doubts or annoying questioning from Reviewer #3, we throw in a few additional albeit arbitrarily selected scenarios in a local sensitivity analysis. If we were throwing a rave party in the early 2000s, LCA showed up wearing tight white jeans, a fluorescent pink sleeveless shirt, glam makeup, and hair of the 1980s.

In this contribution, we will show with examples how Global Sensitivity Analysis (GSA) and Bayesian approaches (see e.g. Saltelli and Ravetz, 2022) can dress LCA up more appropriately for the parties of the post-normal science era (and maybe even the post-truth era). We will assess the shortcomings of some of the commonly used (and abused) techniques to handle incertitude in the field of LCA, and with a friendly wake-up call kindly nudge the community to look outside itself, handle incertitude, and make LCA great again.

Guiding Technology Development for Economy-Wide Decarbonization with GREET Life Cycle Analysis and Scenario Modeling

Tuesday, 4th July - 10:15: LCA methods 1 (A0.51 KOG)

Troy Hawkins [1], ***Uisung Lee*** [1], ***Farhad Masum*** [1], ***Pahola Thathiana Benavides*** [1], ***Saurajyoti Kar*** [1], ***Doris Oke*** [1], ***Udayan Singh*** [1], ***Peter Chen*** [1], ***Tai-Yuan Huang*** [1], ***Chris Kolodziej*** [1], ***Taemin Kim*** [1], ***Michael Wang*** [1]

1. *Systems Assessment Center, Argonne National Laboratory*

Society is in the midst of a massive shift to a decarbonized economy involving replacement of current technologies and difficult choices regarding investments in low-carbon production capacity and new infrastructure. The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model was developed with the support of the U.S. Department of Energy to guide the development of low carbon and sustainable technologies. GREET has been used by stakeholders for determining subsidies based on the life cycle carbon intensity of fuels and energy systems by stakeholders such as the State of California. Recently GREET has been identified in the U.S. federal Infrastructure Reinvestment Act for determining credits associated with hydrogen and clean fuels. This presentation will discuss recent modeling activities in GREET to guide the transition to a decarbonized and sustainable economy. First, we will discuss life cycle analysis (LCA) modeling in support of the development and commercialization of sustainable aviation and marine fuels. This research has contributed to standardized life cycle greenhouse gas (GHG) factors for aviation fuel pathways for the International Civil Aviation Organization's (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) and is guiding the development of LCA guidance for marine fuels for the International Maritime Organization (IMO). The presentation will also discuss ways in which the GREET model is being leveraged and extended to provide additional perspectives on sustainable systems consistent with economy-wide decarbonization. In one study, we consider the material flows of polyethylene terephthalate (PET) and the effect of rewiring these flows via chemical recycling processes (methanolysis and hydrolysis) to decrease waste plastic flows and increase circularity. This study identifies opportunities for returning low quality PET and polyethylene from sources such as clothing and carpet fiber to the top of the downcycling cascade and highlights the need for research to further improve chemical recycling processes to decrease energy use and GHG emissions. We will also describe the Decarbonization Scenario Analysis Model and Bioeconomy Air, Greenhouse Gases, and Energy (Bioeconomy AGE) Model, which enable analyses of alternative technologies considering the allocation of limited biomass and waste resources and matches multiple coproducts with end use markets. This framework compliments LCA studies by presenting the results in the context of economy-wide impacts in a way which can be obscured by functional-unit-based results. Finally, we will discuss the framework we have been using to harmonize LCA and technoeconomic analysis to calculate the marginal cost of GHG avoidance across competing potential uses of waste and biomass resources.

Future resources

Decoupling global environmental pressures from economic growth and human wellbeing: a preview of results of the Global Resources Outlook 2024

Tuesday, 4th July - 09:00: Future resources (B0.31 KOG)

Heinz Schandl [1]***, Detlef van Vuuren*** [2]***, Petr Havlik*** [3]***, Yingying Lu*** [1]***, Sebastiaan Deetman*** [4]

1. *Commonwealth Scientific and Industrial Research Organisation (CSIRO),,* ***2.*** *PBL Netherlands Environmental Assessment Agency,* ***3.*** *IIASA,* ***4.*** *Deetman@cml.leidenuniv.nl*

We present novel results from the scenario modelling work for the forthcoming International Resource Panel Global Resources Outlook 2024 and compare global material use and GHG emissions for a baseline scenario based on SSP2 population , urbanisation and economic trends with a sustainability scenario which introduces ambitious policies for resource efficiency and policies supporting sustainable consumption and production in climate and energy, land, water and food, and shelter and mobility. In the sustainability scenario we include a SDG uplift for food, nutrition, housing and mobility through a global resource and carbon dividend and ensure no net economic loss from sustainability policies to enable a just transition to a global low carbon and circular economy. The scenario analysis is based on an integrated environmental economic modelling approach. We employ a multi-model framework which includes three well established global models. The CSIRO Global Trade and Environment Model (GTEM), the IIASA Global Biosphere Management model (GLOBIOM) and the PBL Integrated Model to Assess the Global Environment (IMAGE). We also integrate a technology-based stock and flow analysis for assets in the provision systems. We report trends for economic development, material use and GHG emissions from 2020 to 2060 for the seven UN world regions and four World Bank country income groups. Our results demonstrate that economically attractive opportunities for reducing material use and GHG emissions exist and that well-designed policies can reduce global material use by a about 25% and can keep global warming within 2 degrees of warming. Material use is reported for all aspects of material flow accounts including domestic extraction, trade, and material footprints. GHG emissions are reported for all relevant greenhouse gases and sectors. The modelling shows that achieving a sustainability transition of the proportions of the sustainability scenario will not happen spontaneously but will require a massive, concerted effort of government, industry and community. The scenario modelling for the Global Resources Outlook is a good example of positioning industrial ecology research in a sustainability science context evaluating the physical, economic and policy implications of the global resource efficiency and greenhouse gas abatement effort.

Quantifying material demand for the global solar photovoltaic supply chain in the terawatt era

Tuesday, 4th July - 09:15: Future resources (B0.31 KOG)

Chengjian Xu [1]***, Olindo Isabella*** [1]***, Malte Vogt*** [1]

1. *Delft University of Technology*

Increasing and large-scale deployments of photovoltaic (PV) systems are needed for a decarbonizing energy system. This is a key for achieving Paris Agreement Goal to limit global temperature increase well below 2 degrees. Here we review state-of-art scenarios projecting future solar PV deployment until 2050, based on different growth scenarios like International Energy Agency, Integrated Assessment models like Image, as well as other literature sources. We select the two PV deployment scenarios, which depict the future most likely range of PV deployment size between about 20 and 70 TWp until 2050.
Photovoltaic research and development focused on reducing levelized cost of electricity (LCOE) mainly through increasing efficiency and reducing production costs. Various technologies at different technology readiness levels have been proposed, including silicon solar cells, thin-film solar cells, III-V solar cells, and other so-called next-generation solar cells. Silicon solar cells are still today's vast majority (around 95%) and this trend is expected to continue into the next decade because of the superior efficiency, lifetime, and cost of silicon solar cells. Here we build up a conservative solar PV technology scenario that entails the dominating utilization of silicon solar cells in the market.
We apply the method of dynamic material flow analysis (MFA) to solar modules. This model estimated the future total stock and flows of solar modules considering a lifetime of 30 years. Further, considering the material composition of different PV technologies, we estimate the material demand and end-of-life (EoL) materials when PV modules are out-of-service. Here we consider different PV deployment sizes and PV technology scenarios. Critical, scarce, and high value materials such as silicon, silver, aluminum, and copper are the research focus of this study. Other materials, which dominate PV modules volume and weight wise such as solar glass and polymers are also within the research scope. Results give projections of the demand for these materials as well as the recycling potential of these materials. Comparing the results of different scenarios allows the discussion of the implications of PV development on raw material use and promotes the guidance policy on sustainable resource use for solar PV.
We find that increasing the raw material production capacity along the supply chain of solar PV in the short-term is needed for securing the rapid deployment of solar PV, which can be challenging. Increasing production efficiency and decreasing the material intensity of solar modules can reduce demand for primary materials significantly. Current EoL PV materials are small/negligible compared to primary material demand, thus only after 2-3 decades closed-loop recycling can offer increasing and considerable potential to offset primary material demand.

Estimating material use in the Netherlands in 2030 on the basis of physical supply-use tables; the appropriate level of detail

Tuesday, 4th July - 09:30: Future resources (B0.31 KOG)

Arjan de Koning [1], ***S. Cap*** [1], ***L. Scherer*** [1]

1. *Leiden University, CML*

The Dutch national government has an interest in the future development of materials use in the Netherlands to evaluate its progress on the Circular Economy (CE). For this purpose, a time series (2010 - 2020) of detailed physical supply-use tables (PSUTs) compiled by the Dutch National Statistical Agency (CBS) is available. These PSUTs can be combined with information on population growth, economic development, energy transition, material use efficiency to create a material use scenario model. The question arises how the future development of materials use can best be modelled.

Using the time series of detailed physical supply-use tables we explore different scenario models that estimate material use over the period 2010 – 2018 based on the material use in 2010 combined with macro-economic data for the same time period. Based on the comparison between observed material use and estimated material use we can get a better idea which scenario modelling approach works better for estimating material use in the Netherlands. These scenario modelling approaches can subsequently be used for estimating material use in the Netherlands in the future.

The novelty of this research is the utilization of the detailed physical-supply use tables containing 500 product groups and 129 sectors and the use of a scenario model that estimates time series of new physical-supply use tables at the same level of detail, based on a reference detailed physical-supply use tables plus macro-economic input parameters. The same scenario modelling approach can be used to make global scenarios of emissions and material use and demand. This research helps to verify the correctness this scenario modelling approach.

The circular economy and upscaling potential of modular floating structures for urban development offshore

Tuesday, 4th July - 09:45: Future resources (B0.31 KOG)

Gil Wang [1]***, Tomer Fishman*** [2]***, Lieke Bikker*** [3]***, Sebastian Schreier*** [4]

1. *Coastal and Marine Engineering Research Institute - CAMERI,* ***2.*** *CML Leiden,* ***3.*** *Leiden University,* ***4.*** *TU Delft*

Every year more than a thousand ocean-going cargo vessels are beached and dismantled on the shores of Bangladesh, India, and Pakistan, which totals approximately 80% of all end-of-life ships. Unfortunately, the reasoning behind this action is simple: on one hand, the global merchant fleet uses these venues as the drop-off zones for end-of-life ships – as they can avoid stringent ship recycling conventions and sell the ship for scrap. And on the other, the local recycling yards thrive on the backs of an unskilled workforce and the environment, as the implementation of local laws is poorly executed. This is a flourishing economic model, entirely based on the absence of environmental regulations and labor rights.

Our research offers to repurpose some of these old tonnages and convert them into modular floating breakwaters, to enable a range of sea space utilization projects, and to alleviate some of the pressure from highly developed coastal areas. However, still little is known about the impacts of floating breakwaters and sea space utilization, and whether reuse is better than current end-of-life solutions. More explicitly, what are the Lifecycle impacts of diverting retired ships from scrap to floating breakwaters, and what are the Lifecycle impacts of that consequence on the scale of the current and future merchant fleet? To answer these questions, using the Shared Socio-economic Pathways (SSP) and GIS analysis, this study aims to examine the upscaling effects of these two alternatives for end-of-life ocean-going cargo vessels. In addition, the study explores the value provided by these yards (resources), the pressure on the environment (human health and eco-system), and the associated effect of floating breakwaters. The results of this study could inform the maritime sector, urban and coastal planners, and policy makers in regard to new alternatives to shipbreaking vis-à-vis coastal developments worldwide.

A Top-Down approach for downscaling sectoral emission budgets. A case study of Canada's construction sector

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 10:00: Future resources (B0.31 KOG)

Hatzav Yoffe [1]***, Keagan Hudson Rankin*** [2]***, Christian Bachmann*** [3]***, I. Daniel Posen*** [1]***, Shoshanna Saxe*** [1]

1. University of Toronto, 2. University of toronto, 3. University of Waterloo

The world's growing population is demanding massive construction of buildings, infrastructure and services, which in turn, results in significant primary resource consumption (e.g. steel, concrete, wood) and associated greenhouse gas emissions (GHG). Global construction is already responsible for >12 Gigatons (20%) of annual GHG emissions[1], a number that is rapidly growing[2]. In line with the Paris agreement, Canada has committed to cutting GHG emissions in half (46%) by 2030[3], heavily constraining the allowable emissions for construction. This reduction is challenging considering the immense construction required in the coming years due to substantial infrastructure renewal needs and Canada's projected population growth. While material industries are exploring low GHG manufacturing pathways, large-scale decarbonization will take time, and materials manufacturing will remain a large emission source in the coming decades.

A key challenge in Canada, and other fast-growing countries, is building the necessary infrastructure that provides equality and dignity to a growing population while rapidly reducing the GHG emissions associated with the construction sector. While a qualitative understanding of 'we must build more while emitting less' is increasingly common, its tensions are under-investigated and practical guidance on how to proceed slimmer still. Quantitative understandings of the construction sector footprint within the total emission budgets are extremely limited[4], inhibiting our ability to update what and how we build or plan future construction. This is exacerbated by the absence of construction as a sector within the United Nation's Intergovernmental Panel on Climate Change (IPCC) national emission reports.

This presentation will explore: 1) estimating current GHG emissions in the construction sector; and 2) establishing future construction sector GHG emissions budgets considering potential tradeoffs with other sectors, using Canada as an example case study.

The study analyzed Canada's construction sector emissions using 'Open IO Canada'[5], an Environmentally-Extended Input-Output (EEIO) model, which evaluates the environmental impact of economic sectors based on high-resolution national statistics paired with pollution release datasets. This IO approach, which facilitates upstream and imported emissions, was applied after failed attempts to back-calculate the construction emissions from Canada's IPCC national report (which will also be briefly discussed). The second part of the study explores pathways to achieve Canada's emission reduction goals by a.) Preserving the construction sector's current share of emissions; and b.) allowing construction emissions to grow by advancing emission reductions in other sectors (e.g. transportation, energy).

Preliminary results suggest that construction emissions are 13% (90MTCO2e) of Canada's total emissions. Specifically, we found *Residential Construction* to be, by far, the largest contributor of GHG emissions nationwide (39%), more than *Transit Infrastructure* (12%), *Office and Commercial Buildings* (6%), and *Industrial Buildings* (3%). Furthermore, in Canada's densely populated and most emission-contributing provinces (Quebec, Ontario, British Columbia), residential buildings make up at least half of the construction emissions.

The study demonstrates the use of EEIO to calculate the construction sector's footprint, including both subsectoral and spatial emissions disaggregation. The study further explores real limitations in terms of GHG budgeting for future construction, as well as emphasizing the importance of downscaling emission budgets to a regional and city level and translating it into carbon-aware planning and development strategies.

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Modelling the regional transformation to hydrogen-based green steel: An integrative and prospective material flow analysis of the North Rhine-Westphalian steel industry

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 10:15: Future resources (B0.31 KOG)

Rainer Radloff [1], ***Ali Abdelshafy*** [1], ***Grit Walther*** [1]

***1.** Chair of Operations Management - RWTH Aachen University*

The production of primary steel is characterized by a high emission intensity. Due to its high coal consumption, the steel industry is responsible for around 30 % of industrial greenhouse gas emissions and thus for 5 % of total German emissions. In North Rhine-Westphalia, steel production accounts for up to 30 million tonnes or even more than 10 % of the state's total emissions. The enormous coal consumption is not only due to the high energy demand, but also to the process-related coal dependency of the classic blast furnace process.

For a far-reaching decarbonisation of the North Rhine-Westphalian industry, the introduction and rapid diffusion of new technologies and processes in steel production is essential. Two approaches are feasible: one is to maintain existing processes with retrofitted Carbon Capture and Usage or Storage, and the other is to avoid emissions through process changes (i.e. Carbon Direct Avoidance). Herein, direct reduction has emerged as a promising Carbon Direct Avoidance technique in the steel industry. All major German steel producers have announced specific steps to substitute coal-based feedstocks by switching to hydrogen-based direct reduction processes. If the hydrogen production and utilization of the steel producers are supplied by renewable energy sources, emissions can be largely avoided. However, this path is associated with far-reaching technical and procedural changes as well as a substantially increased demand for renewable electricity.

Hence, this study presents a case study from Western Germany via quantifying the changes in the regional material and energy flows in the state of North Rhine-Westphalia until the planned decarbonisation in 2045. The quantitative analysis firstly presents a detailed material and energy flow model that depicts the existing supply chain of the regional industry and intersectoral relations. Thereafter, a detailed process simulation model of hydrogen-based steel production is developed according to the industry's detailed technological plans to track the regional impacts of such a transformation to achieve zero-emission steel. In combination with different assumptions on the availability of green hydrogen and complementary climate reduction measures, the results of the process simulation are integrated into the material and energy flow model to map possible stepwise transformation paths until 2045. Here, the analyses show that with a maximum focus on hydrogen, more than 47 TWh of electricity from renewable energies could be required per year for these structural changes. Consequently, our work quantifies different approaches by which the decarbonization of the steel industry can be achieved with lower amounts of renewable electricity. For example, partial reliance on natural gas as a reducing agent in combination with the use of CCUS technologies can significantly reduce electricity demand for the transformation, especially in the medium term.

Buildings & Infrastructure 2

Forecasting embodied housing emissions and material efficiency scenarios in Ontario, Canada.

Tuesday, 4th July - 09:00: Buildings & Infrastructure 2 (B0.41 KOG)

Keagan Hudson Rankin [1], ***Aldrick Arceo*** [1], ***Hatzav Yoffe*** [1], ***Kaan Isin*** [1], ***Shoshanna Saxe*** [1]

1. *University of Toronto*

This work forecasts possible embodied housing emission pathways under different material efficiency scenarios using detailed, bottom-up data. Communities around the world are facing a housing deficit and associated demand to build more. In parallel, this demand for housing is driving a large and accelerating growth of embodied emissions from construction materials. Global construction norms, if they persist, will make meeting carbon reduction goals impossible. The province of Ontario, Canada exemplifies this challenge; residential buildings account for 45% of Ontario's construction emissions. The province has committed to reducing GHG emissions 30% below 2005 levels in ten years, while also committing to building 1.5 million homes in the same time. A quantitative understanding of this conflict, and actionable strategies for building more with less emissions, are needed. Past projections of embodied construction emissions have focused on high-level, top-down, typology-based methods that may not capture variability in construction or inform specific design and policy recommendations. In this study, we develop a bottom-up forecasting model of embodied housing and associated local infrastructure emissions in Ontario, Canada. The forecasting model uses open infrastructure data as well as two recently-developed databases on building material use (Guven et al., 2022) and GHG emission factors (Arceo et al., In Review), along with 43 additional building material quantifications. Monte Carlo sampling and machine learning regression are used to forecast embodied emissions under several material efficiency scenarios. Results indicate that housing construction is a main driver of embodied emissions, with a single-family construction increasing emissions in housing, roads, and water infrastructure. Constructing low-rise multi-unit residential forms instead of single-family homes could reduce kgCO2eq/bedroom by up to 39%, and optimizing the design of both forms could induced up to 62% savings. Potential reductions through material technology and process improvements are less than those achieved through changes in building design and neighbourhood form. Our work also introduces the concept of the housing sandwich: the range of future construction scenarios in which a city is able to provide enough suitable housing for their growing populations (the lower bound) while also limiting their material emissions to be in line with climate commitments (the upper bound).

Arceo, A., MacLean, H., & Saxe, S. (n.d.). *Embodied greenhouse gas emissions intensity of single-family dwellings: data uncertainty, influential parameters, and variability between Toronto, Perth, and Luzon.*

Guven, G., Arceo, A., Bennett, A., Tham, M., Olanrewaju, B., McGrail, M., Isin, K., Olson, A. W., & Saxe, S. (2022). A construction classification system database for understanding resource use in building construction. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01141-8

Promoting Actionable Science for Urban Sustainability

Tuesday, 4th July - 09:15: Buildings & Infrastructure 2 (B0.41 KOG)

Jens Peters [1], ***Matan Mayer*** [2], ***Santiago Perez Rodriguez*** [3]

***1.** University of Alcalá, **2.** IE University, **3.** University of Technology of Troyes, France.*

Today, more than half of the world's population is considered urban. Cities, the epitome of modern human existence, are the spaces where most people consume, share and produce resources. Cities are therefore intense consumption and production geographies inherently related to the unsustainability crisis. Urban sustainability studies deal with the impacts of these large systems. Such studies can play a crucial role not only in reducing the environmental impact of cities and its dwellers, but in promoting more sustainable urban spaces; from promoting efficient use of resources through sustainable policies and practices, to encouraging new ways of living within urban spaces while regenerating its natural commons. However, urban sustainability research often remains on a theoretical level and lacks applicability and thus impact.

To respond to such a problem, the non-profit AScUS (Actionable Science for Urban Sustainability) proposes and promotes safe spaces to take the theory into action. Since 2020, AScUS has been using inter and trans-disciplinary approaches to encourage its participants to generate actions to repair and regenerate the natural and social tissues of cities around the globe. The activities (such as the un-conferences) promote all kinds of actionable components to put in practice solutions to fight the unsustainability crisis from the cities, i.e., contain some practical applicability or value for stakeholders involved in decision making processes.

AScUS arose from a voluntary initiative out of the Metabolism of Cities network with the idea of promoting more actionable science related to urban sustainability. It started with the idea of organizing a conference with an alternative format, giving rise to the first AScUS unconference in 2020. Since then, further activities were initiated by IS4IE members on a voluntary basis and, since 2022 AScUS has consolidated into a non-profit organization registered in France.

Its flagship activity is a bi-annual AScUS Un-conference, a participant-driven event with workshops and discussion sessions directed at developing concrete path-to-action documents. These path-to-action documents are the tangible outcomes from the Un-conferences. Those outcomes could be directly translated into actionable research to inform academics and practitioners of possible solutions to particular urban issues. Actions coming from AScUS can help to target solutions to larger urban issues contributing to the regeneration of the planetary boundaries and the restoration of socially sustainable places for city-dwellers.

This contribution presents the latest activities of the AScUS initiative and their most important outcomes, such as the foundation of the non-profit organization, publications and activities. It showcases some of the most important (actionable) outcomes until today and expands on the foreseen future activities and possibilities to get involved further.

Assessment of climate change mitigation potential of wood-based construction and textiles

Tuesday, 4th July - 09:30: Buildings & Infrastructure 2 (B0.41 KOG)

Elias Hurmekoski [1]***, Janni Kuntu*** [1]***, Tero Heinonen*** [2]***, Timo Pukkala*** [2]***, Heli Peltola*** [2]

1. *University of Helsinki,* ***2.*** *University of Eastern Finland*

Wood use is expanding to new markets, driven by the need to substitute fossil-intensive products and energy. Wood products can contribute to climate change mitigation, if they have a lower fossil footprint than alternative products serving the same function. However, the climate change mitigation potential is contingent on the net fossil and biogenic emissions over time, as well as the realism of the counterfactual scenario and market assumptions. This study aims to improve the consistency of assessing the avoided fossil emissions attributed to changes in wood use, and to estimate the additional mitigation potential of increased wood use in construction and textile markets based on wood harvested in Finland.

The results show that the substitution impacts of wood use are not large enough to compensate for the reduction in forest carbon sinks in the short and medium term. This outcome is further aggravated, considering the decarbonization of the energy sector driven by the Paris Agreement, which lowers the fossil emissions of competing sectors more than those of the forest sector.

Further, we present an approach based on microeconomic theory and econometric modelling for identifying the existence and rate of substitution, taking the case of textiles. The results point to wood-based textiles being imperfect substitutes for cotton with an empirical substitution ratio of 13-34%, and mostly independent from the demand for synthetic fibers with an empirical substitution ratio of 0-18%. With a substitution ratio of 1:1, the marginal substitution impact would be -2.17 tCO_2eq. avoided per tonne of wood-based fibers produced. With the empirical substitution ratios, an additional unit of wood-based fibers produced may lead to an increase of fossil emissions, ranging from -0.27 to 0.62 tCO_2eq./t. The explanation is that only part of the RCF supply replaces alternative materials, while the rest merely increases overall textile supply and thereby the overall fossil emissions. The empirical substitution ratios point to historical evidence, and may not necessarily reflect future market conditions, given evolving product properties, prices, and preferences. For example, for novel wood-based textile fibers, the substitution ratio may be higher and the fossil emission lower. The empirical substitution ratio can, however, be used as a reasonable baseline for identifying substitute products and the closeness of the substitutes.

The trade-off between short-term and long-term net emissions creates a strong motive to pursue shifts in the end uses of wood products and to improve resource efficiency, so that the average substitution impact can be increased without negatively affecting forest carbon sinks. The study concludes by discussing the necessary scale and feasibility of such shifts. For example, for wood construction, the demanded volumes may be small enough that shifts in product portfolios could likely be covered by changes in forest management to increase the share of logs in roundwood production. Also, by-products can be shifted from direct energy use to material uses such as pulp or panels, provided that the alternative energy source to cover the operational energy demand of wood product mills has no fossil emissions.

Keywords: substitution; climate change mitigation; textile markets; construction markets; avoided fossil emissions; wood products; life cycle assessment

High-Resolution Mapping of the Material Stocks in Buildings and Infrastructures in China

Tuesday, 4th July - 09:45: Buildings & Infrastructure 2 (B0.41 KOG)

Bowen Cai [1] ***, Helmut Haberl*** [2] ***, Dominik Wiedenhofer*** [3] ***, Zhenfeng Shao*** [4]

***1.** School of Remote Sensing and Information Engineering, Wuhan University, **2.** University of Natural Resources and Life Sciences, Vienna, **3.** University of Natural Resources and Life Sciences, Vienna (BOKU), **4.** State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing*

Material stocks (MS) in buildings and infrastructures serve as a crucial backbone for the social metabolism. China, the world's largest developing country, is going through a period of rapid urbanization and fervent construction activities, making it a global hotspot of resource use and MS accumulation. Previous research for China so far mapped stocks either for single cities and regions, for specific stock types, or at relatively coarse resolution. It was difficult to accommodate both larger scale and finer resolution. Quantifying the spatial patterns of the entire MS for the whole of China at high resolution is therefore an important next step.

The rapid development of remote sensing technologies and the availability of simultaneous multi-source data have greatly promoted earth observation research, which also enables characterizing the spatial distribution of built environment stocks at high resolution. Methods for MS mapping generally employ a data-based "bottom-up" approach, such as Nighttime light (NTL), Building Information Model (BIM), and Geographic Information Systems (GIS) data. However, they are unable to balance between the diversity of the built environment at high spatial resolution and the generalizability of a large study area.
In the research we are going to present, we developed a 'Volume-Age-Function-Location (VAFL)' based 10m-resolution MS model for China, including material intensity (MI) factors to quantify the mass of materials accumulated. The VAFL model relies solely on publicly available Sentinel-1/2 remote sensing images and crowd-sourced data from Open Street Maps. Given the vast quantity of data required, three urban agglomerations in diverse geographical locations were selected as the first case studies to train and validate the modeling. Furthermore, results based on NTL and GIS data from the literature are used for comparison with our results at local areas, and the differences between the three approaches are investigated. Finally, using population grid data, the intrinsic characteristics of the interaction between urban MS and human activities are discussed. As a next step, this work will be used to map China's entire MS at 10m-resolution and in this presentation, we discuss challenges and opportunities for such a wall-to-wall mapping of a very large country like China. With this work, we aim to contribute to a better understanding of the potentials for mining the MS at the end of their useful lifetimes in a spatially explicit manner, to investigate the links to socio-economic considerations and services, and further enrich the evidence base for regional spatial development planning.

The environmental impacts of transitioning from fossil-based to agricultural-based feedstocks for cement

Tuesday, 4th July - 10:00: Buildings & Infrastructure 2 (B0.41 KOG)

Alyson Kim [1], ***ELISABETH VAN ROIJEN*** [1], ***Sabbie Miller*** [1]

1. *University of California, Davis*

The high demand for cement and concrete globally is driving notable environmental burdens from their production, particularly CO_2 emissions. As a result, policymaker and industry interest in greenhouse gas (GHG) emissions mitigation efforts for these materials are increasing to meet regional and intergovernmental climate goals. A common technology in cement GHG mitigation roadmaps is to lower its highest emitting component, clinker, the kilned and quenched component of cement. This reduction is typically achieved through the increased use of supplementary cementitious materials (SCMs), a measure functional at reducing the life cycle GHG emissions for cement. However, one of the most common SCMs used is fly ash (a by-product of coal combustion for electricity) and the anticipated decrease in coal electricity production requires investigations into more resilient and renewable SCM feedstocks. Agricultural production often results in residue materials that are not part of the food resource and are not currently of much value. Some of these residues contain desirable mineral compositions, and their ash post-combustion has potential to be an SCM replacement. Additionally, this combustion stage can be used to help meet energy demands either within cement and concrete production or in other sectors. In this study, we build from our prior work on developing an open data concrete mixture environmental impact quantification tool, OpenConcrete. Namely, we explore the potential advantageous effects of utilizing a bio-driven, circular economy approach to resource consumption. Taking advantage of the customizable nature of this tool, here we integrate environmental inventory data to evaluate ashes from agricultural residues (e.g., rice straw ash from rice production, wheat straw ash from wheat production). We then apply this tool adaptation to evaluate the potential range of environmental impacts of some common agriculture residues. As anticipated, the results show the agricultural-based feedstocks to contribute to significant reductions in GHG emissions per kg of cement. Although these are significant decreases to GHG emissions, the agricultural-based feedstock materials must stay within similar replacement levels as fly ash to have desired benefits. In addition to investigating replacement levels, environmental impacts beyond GHG emissions were considered; the source of agricultural feedstock influenced whether these materials led to reductions or increases to ecotoxicity, eutrophication, acidification, energy demand, and particulate matter less than 2.5 microns ($PM_{2.5}$). Further, we highlight the sensitivity of the environmental impacts of agricultural by-products to the allocation method utilized (i.e., considering a portion of the impacts from the primary production processes). These findings are critical to understanding the future impacts of cement, as coal-based fly ash resources continue to decline and the demand in construction materials (particularly in cement demand) grows.

Drivers and barriers of plastic circularity in the construction industry - the case of Sweden

Tuesday, 4th July - 10:15: Buildings & Infrastructure 2 (B0.41 KOG)

Shuang Wang [1], ***Leonardo Rosado*** [1], ***Maud Lanau*** [1], ***Magnus Österbring*** [2], ***Holger Wallbaum*** [1]

1. Chalmers University of Technology, 2. NCC Sverige AB

Across Europe, energy recovery incineration has become the largest destination of plastic waste since 2014 and 12.4 Mt of plastic waste has been incinerated in 2020. However, almost all plastics are made of fossil fuels, and burning them leads to large CO2 emissions. For example, more than 90 % of the CO2 emissions from energy recovery of waste in Sweden are estimated to come from fossil-based plastics. Furthermore, the production of plastics accounts for approximately 10 % of the global annual usage of fossil fuels. In line with SDG 12 (Responsible consumption and production) and SDG 13 (Climate action), the resource efficiency of plastic circularity needs to be improved. As the second largest consumer of plastics globally, in Europe, and in Sweden, the construction sector can play an important role in that. It accounts for approximately 20 % of plastic consumption in Europe with a variety of plastic products being used for packaging or built in the construction as pipes, floorings, and the like. While previous research has investigated the potential of using secondary plastics in construction, such as recycling plastics and fly ash for construction bricks, the plastic circularity in the construction sector remains critically low, for instance, the recycling rate of plastics in the Swedish construction sector is only 0.8 % according to a report published by Swedish Environmental Protection Agency in 2022. This shows that recycling plastics from the construction sector is barely explored.

Taking the buildings in Sweden as an example, as they contain diverse plastic products, this study aimed to understand the potential for improving the resource efficiency of plastics in the construction sector by identifying the drivers and barriers in the value chain. A broad set of drivers and barriers was collected through a literature review. Looking into the functional and material (i.e., polymer) characteristics of different plastic products allowed for an improved specification of drivers and barriers.

The resulting set of drivers and barriers are divided into 5 categories: information, material, actor, analytic, and business/service. It illustrates the fragmentation and lack of a holistic perspective in the value chain of plastics in the construction sector. These five divides are interrelated, one driver or barrier can be assigned to several divides at the same time. The lack of traceable digital product information is an example of the barriers, which covers information, actor, and business/service. Deficient cooperation of actors along the value chain, missing information about the properties and proper sorting and recycling process of plastic products, and the absence of the service providing an information platform are responsible for this barrier. Understanding the functional and material characteristics of different products helps to indicate the drivers and barriers when recycling one specific plastic product or polymer. Plastic pipes have a variety of applications in the building, e.g., potable water supply and radiator connection. Compared to potable water supply, pipes used for radiator connections have requirements for resistance to oxygen diffusion and are equipped with an oxygen diffusion barrier of Ethyl Vinyl Alcohol. Therefore, pipes for radiator connection contribute to the barrier, namely the multi-layer composition of plastic products. These findings will be used as input for further research on improving the resource efficiency of plastic circularity.

New questions, new methods

CO2 utilization from biomethane production in Europe: potential and assessment of alternatives

Tuesday, 4th July - 09:00: New questions, new methods (B0.25 KOG)

Stephanie Cordova [1], *Marcus Gustafsson* [1], *Mats Eklund* [1], *Niclas Svensson* [1]

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Many products in daily life require carbon structures, and thus a decarbonization of the economy is not possible. Instead, it is necessary to talk about defossilization, where sources of biogenic CO_2 and carbon capture and utilization (CCU) strategies are vital to replace fossil carbon. Biogenic CO_2 is a by-product of biomethane production from anaerobic digestion, where it is removed to increase the energy density of the gas. It is considered a waste and usually emitted to the atmosphere, although with its high purity, it could replace CO_2 in traditional applications or carbon conversion routes under development. Therefore, this research studies the feasibility of incorporating CCU principles in biomethane production and evaluates the potential performance of this practice. To evaluate the feasibility, the potential production of CO_2 from biomethane in Europe was quantified for 2020, 2030, and 2050. Key aspects for the integration of CCU with biomethane production in the short- and mid-term were identified and evaluated using multi-criteria analysis (MCA) with environmental, technical, economic, and social criteria. Also, the climate performance of biomethane production with CCU was analyzed, considering that the main goal of CCU is to reduce the climate impact.

Results show that 3.7 Mt of CO_2 from biomethane production could potentially be obtained, a value that could reach 43.6 Mt in 2030 with the RePowerEU strategy and 118.2 Mt in 2050 exploiting the available sustainable biomethane feedstock in Europe. Employing methanation technologies to convert the CO_2 into additional methane would increase the biomethane production by around 60% assuming full conversion. Other available alternatives with high maturity levels and low dependence on fossil fuels include horticulture, the production of mineral carbonates, syngas fuels, pH control agents, bulk chemicals like methanol, and liquefied CO_2 for direct use in refrigeration, food industry, or concrete curing. The indicators employed in the MCA provide information to identify feasible alternatives that can be incorporated with biomethane plants and provide insights for possible collaboration with other actors. For instance, the production of liquefied CO_2 is feasible for short-term application but could face some regulatory and technical barriers, meaning additional costs and energy requirements for purification and liquefaction steps. Moreover, methanation enables additional substitution of fossil fuels, reducing the climate impact. The main drawback is its high energy requirement for hydrogen production, which could limit its implementation. The production of mineral carbonates allows the delay of emissions due to its storage capacity and does not require CO_2 of high purity. Nevertheless, it could require the CO_2 to be transported long distances to reach the production locations and might increase capital and operational costs for the user. Regarding the climate performance of biomethane with CCU, the results show a possible reduction of climate impact depending on the technology and avoided products. Methanation with green H_2 and concrete curing would be the best options from a climate perspective, while some reduction of the climate impact is also possible with other alternatives compared to biomethane production without CCU. The studied alternatives allow a reduction of emissions for the system and confirm that CCU in biomethane systems is a tool for defossilization in the future.

Unraveling the impact of using alternative carbon sources in existing petrochemical clusters

Tuesday, 4th July - 09:15: New questions, new methods (B0.25 KOG)

Andrea Ramirez [1], ***Mar Perez-Fortes*** [1], ***Paola Ibarra Gonzalez*** [2], ***Michael Tan*** [1], ***Tonny Manalal*** [1], ***Inna Stepchuk*** [1]

1. Delft University of Technology, 2. Technical University Delft

Ninety percent of raw materials used in the EU chemical industry are of fossil origin. A future industrial system that is independent of fossil resources will require the use of alternative carbon sources (ACS), such as CO_2 or biomass, to produce chemicals and materials. Industrial clusters are, however, complex systems with many and increasingly intertwined processes where interventions in any single process can affect other processes (possibly operated by other firms). There is, however, limited knowledge on the potential impact of deploying ACS processes that will be embedded in existing symbiotic industrial clusters. Without this knowledge, the use of ACS could unintentionally result in industrial systems that are more complex, less resource efficient, and produce more emissions. To address this gap, we are developing and testing a conceptual framework that combines ex-ante technology assessment and industrial symbiosis to understand cascading impacts in today's industrial clusters. In this presentation, an overview of the methodology and intermediate results of the 5-year project UNRAVELING (2019-2024) will be presented.

In the first phase of the project, which has been completed, we developed a bottom-up model of a representative petrochemical cluster based on existing conditions in the Port of Rotterdam (PoR) in the Netherlands. The model includes 54 fossil base chemical processes (corresponding to 20 companies). Each individual process has been modeled at the process level using Aspen Plus, mimicking the characteristics of the existing plants in the PoR (e.g, in terms of type of products, technology routes, capacities, and utilities). This approach allows getting detailed energy and mass balances as well as equipment lists and area footprints. Further, we identified and included in the model existing interactions between chemical processes in terms of product, energy (steam, electricity), waste and other utilities (e.g., argon, oxygen, hydrogen). The model is based on public information (reports, permits, websites, and interviews with stakeholders) and is representative of the complexity of the petrochemical cluster. In the second phase of the project, which is currently in progress, we are modeling (at a similar level of detail to the baseline) novel technologies that use ACS and will then be implemented in the cluster to replace the fossil base alternative to identify and evaluate potential cascading impacts from their implementation. We have started by focusing on one chemical building block (ethylene) and one downstream derivative (MTBE). For ethylene, from 69 potential ACS routes that were identified, 3 were selected for further modeling: direct electrochemical conversion of CO_2 to ethylene; biomass steam gasification combined with Fischer Tropsch and PE low-temperature pyrolysis. For MTBE, there are less ACS routes available, and a biomass-to-isobutanol-to-MTBE synthesis process was selected. For both chemicals, we assess KPIs at process level (e.g, efficiency, carbon footprint, water demand, LCOP) as well as KPIs at value chain and cluster level (e.g., ACS use efficiency, net change in energy and water demand, change in the structure and complexity of the cluster). UNRAVELING's approach will generate insights into the resource, energy and costs impacts of defossilizing multiple and interconnected value chains and support identifying which defossilization strategies could result in larger gains.

Utilization of Machine Learning for Satellite Image Analysis: the Land Use Change Induced by Copper Mining

Tuesday, 4th July - 09:30: New questions, new methods (B0.25 KOG)

Junbin Xiao [1], Yoko Yamakata [2], Takeshi Komai [1], Kazuyo Matsubae [1]

1. Graduate School of Environmental Studies, Tohoku University, 2. Graduate School of Information Science and Technology, The University of Tokyo

Following the fossil fuel, land use change (LUC) induced by agriculture, deforestation, mining, and other human activities has become the second-largest contributor of greenhouse gas emission [1]. However, unlike CO_2 emissions, water consumption and other indicators which have been broadly investigated in life cycle assessment (LCA), LUC has not been properly evaluated yet and only the global average data is used in LCA [2] due to the deficiency of space-specific evaluating method and data.
Based on the multitemporal, multispectral, multiresolution characteristics, satellite images are expected to be utilized for spatial analysis like LUC in mining activities. However, because of the huge volumes of data and lack of analyzing methods, LUC was evaluated by many researchers manually, which is time- and labor-consuming with limited output. Fortunately, the rapid development of image recognition in machine learning provides a possibility for comprehensive assessment of LUC induced by mining activities.
Copper is an indispensable resource for modern human society. As forecasted, copper demand will increase dramatically because of the decarbonization and energy transition [3]. On the other hand, the life cycle of copper, is accompanied by LUC, energy and water consumption and other socio-environmental impacts. With the continuous extraction, copper ore grades keep declining in recent decades, leading to larger environmental impacts by copper production. Land use change intensity (LUCI), which indicates the amount of changed land cover behind per unit of copper production, has not been investigated properly yet.
Therefore, in this research our objective is to utilize machine learning for satellite image analysis to evaluate the amount of LUC at copper mining area and LUCI of global copper production, turning the LUC into data for further assessment and visualizing the environmental impact of land use change.
Pix2pix deep learning model using conditional generative adversarial network (CGAN) was applied for satellite image analysis, with U-Net as generator for semantic segmentation. The LUCI was calculated by changed land use area (km^2) obtained from satellite image analysis, integrating with operational data of annual copper production (ton) from S&P database and financial reports.
We found that as the extraction moves on, the LUC keeps increasing while the LUCI tends to decrease gradually, from 0.0096 m^2/kg to 0.0048 m^2/kg, mainly because of the large LUC of open-pit mining activities and relatively low copper production at the initial stage. LUCI of copper production changes over time and varies at different mining sites, indicating that the current average data used in calculation is not suitable and more detailed data is urgently required for land use change assessment. Also, with the application of machine learning, the problem that caused by the unavailability of normalized difference vegetation index (NDVI) in non-vegetated landscape can be solved and relatively accurate (IoU=0.7563) LUC was obtained automatically, while more materials for the deep learning model are required.
As conclusion, machine learning is possible for utilization in satellite image analysis to automatically obtain the area of the LUC induced by mining activities from dozens of satellite images. Except for copper, this method can be utilized for LUC assessment of other mining activities including illegal artisanal small-scale mining.

[1] IPCC, 2014. Climate change 2014: mitigation of climate change. Cambridge University Press, NY.
[2] Nakajima, K. et al., 2017. Science of The Total Environment 586, 730–737.
[3] Watari, T. et al., 2020. Resources, Conservation and Recycling 155, 104669.

Quantifying Biodiversity and Climate Security from Water and Carbon Capture

Tuesday, 4th July - 09:45: New questions, new methods (B0.25 KOG)

***Biji Kurup* [1], *Delwyn Jones* [2]**

***1.** Environmental Wisdom, EN-WIS, **2.** The Ecquate Evah Institute, Tamborine Mountain QLD*

Demand for water and fuel inputs to industrial operations typically arise as process feedstock, or fuel, steam or coolant for power generation. While fuel, feedstock and water-security are vital for production, resource recovery now supersedes waste disposal. This work present literature reviews and case studies of carbon capture and water recycling. It aims to convey the importance of

• climate and water security to maintain natural, community, human, industrial and financial capitals,
• water circularity to meet needs of current and future generations considering climate crises,
• carbon and water circularity sufficient to regenerate natural ecosystems near pre-industrial capacity,
• Clean water, effluent, air, and emissions to maintain safe operating space within planetary boundaries,
• methods for quantifying net-benefit versus net-harm to report evidence of nature-positive outcomes,
• qualifying messages of higher benefits versus lower damages to better communicate outcomes.

Co-located refineries, power stations and factories making mineral, chemical and fertiliser products in the Western Australian Kwinana Industrial Area share resources and infrastructure. Most rely on fossil fuel and primary groundwater drawn, managed and capped by the State regulator. Allocation limits, however, set in 2004, saw industry increased demand on the local 24 Megalitre/day capacity water recycling plant. New production lines for Lithium and other rare earths drove up demand for fuel and process water. Future higher reclaimed supply uptake will be crucial to meet demand for Hydrogen gas fuel from renewably powered electrolysis. To secure higher demand by 2031, Kwinana's annual recycled water capacity is to increase by 52 Gigalitres. The Sepia Depression Ocean Outlet currently dispenses treated wastewater into marine ecosystems 4.1 km offshore 20 km from Perth.

Literature reviews of sustainable water fuel and emissions management methods are discussed. Industrial symbiosis, an industrial ecology subset, generally refers to exchanges between co-located industries of energy, feedstock, by-product and waste-derived material. Many case studies have proven such symbiosis reduces environmental, social and economic loads. Reviews of ecolabelling found quantitative Life Cycle Benefit Assessment (LCBA) showed security and wellness benefits arose beyond Life Cycle Impact Assessment (LCIA) reports of damages. LCIA and LCBA results used International Standard metrics table quantitative indicators. Applications of the Six Capitals Model (SCM) shows carbon capture and water re-use offers business opportunities as well as lower demand for mining, transport, and reduced pollution.

New indicators were developed to assess sustainability benefits from Kwinana case studies. Integrated quantified social capital, ecological damage and ecological benefit assessments depict community wellness and security. Methods and examples show how to more effectively report net-damages and net-benefits without negative bias. The work concludes these methods were practical and more effective for industry and community stakeholders to assess and show benefit than previous sustainable development studies. It shows combined economic and LCA methods can improve communications from environmental science, policy and regulators.

OpenGHGMap And the Roadmap Toward High Spatial Resolution Models of the Economy

Tuesday, 4th July - 10:00: New questions, new methods (B0.25 KOG)

Dan Moran [1]

1. *NTNU*

I present OpenGHGMap, a new GHG emissions inventory based on OpenStreetMap with 700m specific locations and 400,000 administrative regions worldwide. I will also discuss the considerable overlaps between the work of assembling emissions inventories and the work of spatially resolving economic processes which may be of interest for improving spatial resolution in IO and LCA models.

Integrated assessment modeling shows environmental leakage of aggressive decarbonization goals

Tuesday, 4th July - 10:15: New questions, new methods (B0.25 KOG)

***Kaixin Huang* [1], *Matthew Eckelman* [1]**

***1.** Northeastern University*

Many U.S. states have adopted the goal of achieving carbon neutrality in the coming decades. Pathways for achieving these targets would likely yield a reduction of air pollutant emissions as well. This presentation will describe and analyze several state-level decarbonization pathways for Massachusetts (MA), including electrification of buildings and transportation and decarbonization of the electric grid, estimating their impacts on in- and out-of-state emissions of carbon dioxide (CO_2) and several air pollutants. The analysis applies the GCAM-USA integrated assessment model with state-level resolution. We consider interactions between state and regional policies such as the Regional Greenhouse Gas Initiative and the Transportation and Climate Initiative. The most aggressive state decarbonization pathway that was examined would achieve only a 65% of reduction in CO_2 emissions by 2050 relative to 2015, indicating the need for further decarbonization options within the industry and non-road transportation sectors to achieve net-zero emission goal stated by the current administration. The air pollution co-benefits under these decarbonization pathways are significant, especially for primary fine particulate matter. While policies focusing only on MA are shown to produce in-state reductions of CO_2 and air pollutant emissions, a portion of these reductions was countered by emission increases in other states, indicating the need for coordinated regional planning to prevent emission leakage.

Special Session: Alternative Proteins and Cellular Agriculture

Environmental impacts of cellular agriculture

Tuesday, 4th July - 09:00: Special Session: Alternative Proteins and Cellular Agriculture (C1.31 KOG)

Hanna Tuomisto [1]

1. University of Helsinki and Natural Resources Institute Finland (Luke)

Cellular agriculture means the use cell-culturing technologies to produce agricultural products. The products of cellular agriculture are grouped to i) cellular products consisting of the cultured animal, plant or microbial cells, and ii) acellular products consisting of substances produced by microbial cells. For instance, animal cells can be cultured in bioreactors to produce cultured meat that is a cellular product. Similarly, cultured plant cells (Kobayashi et al. 2022) or microbial cells can be used as ingredients for protein-rich food products. Microbial cells can be genetically modified to synthesise specific proteins, such as casein or ovalbumin, or fats (e.g. alternatives to palm and coconut oil). Life cycle assessment (LCA) studies have shown that cultured meat (Tuomisto et al. 2022), microbial proteins (Järviö et al. 2021a) and recombinant casein (Behm et al. 2022) and ovalbumin (Järviö et al 2021b) have lower environmental impacts compared to their animal-based counterparts. However, energy consumption, and especially electricity consumption, can be higher. Climate impact of the cell-cultured foods is highly related to the type of electricity source. The land use requirements of cell-cultured foods are generally substantially lower compared animal-based foods. As the technologies are still under development, the LCA studies have high uncertainty. Especially, the LCA studies of cultured meat are based on modelling of hypothetical large-scale production systems, but there are still many uncertainties related to the process design and nutrient sources. As the replacement of livestock products with cellular agriculture would have major changes in the inputs and outputs of the systems, consequential LCA studies would be needed in order to provide more comprehensive understanding of the environmental impacts of the transition (Tuomisto 2022).

The environmental impacts of a proposed 250kL cultured meat production facility, based on industrial data

Tuesday, 4th July - 09:20: Special Session: Alternative Proteins and Cellular Agriculture (C1.31 KOG)

Benjamin Sprecher [1], ***Tamar Makov*** [2]

1. Technical University Delft, 2. Ben Gurion University of the Negev

Cultured meat, an innovative and sustainable alternative to conventional meat production, has garnered significant interest due to its potential to reduce environmental burdens and provide a viable solution to meet the increasing global demand for protein. This study presents a life cycle assessment (LCA) of a proposed 250kL cultured meat production facility, focusing on the environmental impacts of producing beef through a cellular agriculture process.

The presentation will provide an overview of the methodological choices, including the scope, functional unit, and system boundaries. We will discuss the data collection process, which relies on industrial data obtained from various stakeholders. This data-driven approach ensures that the analysis accurately reflects the current state of the industry.

Our LCA will compare the environmental performance of the proposed cultured meat facility to that of conventional beef production, considering factors such as greenhouse gas emissions, land use, water consumption, and eutrophication potential. The results reveal that the 250kL cultured meat facility significantly reduces environmental impacts compared to traditional beef production for some impact categories, but not all, contributing to the ongoing conversation about the potential of cultured meat as a sustainable food source.

Furthermore, the presentation will identify the key drivers of environmental impacts within the cultured meat production process and suggest potential improvements to further enhance its sustainability. We will also address limitations and uncertainties in the analysis, acknowledging the need for continuous data refinement and methodological advancements to refine our understanding of cultured meat's environmental performance.

Environmental Life Cycle Assessment of Cultivated Meat Burgers

Tuesday, 4th July - 09:30: Special Session: Alternative Proteins and Cellular Agriculture (C1.31 KOG)

Sunghoon Kim [1], ***Bhavik Bakshi*** [1]

1. *The Ohio State University*

The meat industry's environmental impact is a pressing global concern, prompting the urgent search for sustainable alternatives. Cultivated meat, produced through cell culture, has emerged as a revolutionary approach to address the environmental concerns associated with conventional meat production. SCiFi Foods has developed a pioneering cultivated meat burger that has the potential to innovate the food industry. In this comprehensive study, we undertook a life cycle analysis (LCA) to evaluate the environmental impact of this burger in comparison to conventional beef patties and plant-based alternatives currently available in the market. We assessed the life cycle impacts of the cultivated meat burger with the more rigorous assumption (considering the motor yield) by evaluating four critical environmental indicators: greenhouse gas emissions, land use, energy use, and water use. For comparison with other studies, we selected appropriate normalization and weighting factors for evaluation criteria. Our results revealed remarkable environmental advantages of the novel burger, with significantly lower impacts when compared to beef patties. Specifically, the cultivated meat burger exhibited an impressive 87% reduction in greenhouse gas emissions, 39% lower energy use, 90% less land use, and an astounding 96% reduction in water use compared to the comparable beef patty. To further validate our findings, we conducted comprehensive sensitivity analyses to assess the effects of data uncertainty, significant assumptions, and the impact of manufacturing plant location. The results consistently demonstrated that the environmental impact of the novel burger remained consistently lower than the lowest analyzed point in the beef burger, affirming its favorable environmental performance. Furthermore, our findings indicate that if the production facility for the novel burger is installed in 18 out of the 27 eGRID regions in the United States (based on the 2020 year), it has the potential to yield alternative meat with significantly lower greenhouse gas emissions compared to commercialized beef patties. In conclusion, our study demonstrates that the novel cultivated meat burger developed by SCiFi Foods has significantly lower environmental impacts than conventional beef patties and is comparable to current plant-based alternatives. These findings underscore the potential of cultivated meat as a sustainable and environmentally-friendly alternative to traditional meat production, providing valuable insights for future research and development in this field.

Environmental impacts of large-scale industrial production of cultured meat

Tuesday, 4th July - 09:40: Special Session: Alternative Proteins and Cellular Agriculture (C1.31 KOG)

Tamar Meshulam [1], ***Tamar Makov*** [1]

1. Ben Gurion University of the Negev

Livestock-derived products have long provided valuable nutrition to humanity, but are associated with a multitude of negative environmental consequences, including greenhouse gas emissions, water depletion, and extensive land use. Recently, the production of cultured meat (CM) has been put forward as a promising solution that could allow continued meat consumption at substantially lower environmental costs. However, as a relatively new technology, the full extent of CM's environmental implications are not yet fully understood. Prospective Life Cycle Analyses (LCA) suggests that CM could substantially reduce GHG emissions, yet these studies predominantly assess the environmental impact at the product level, and do not explore the potential shift in resource requirements associated with large-scale adoption of cultivated meat. Building on a prospective techno-economic LCA, we examine several scenarios for future large-scale adoption of CM and explore the system-wide implications associated with such shifts in the production and consumption of meat. Our results shed light on potential trade offs between energy and materials in agri- tech and can be used to support evidence-based policy making and help steer the future deployment of meat analogs towards more sustainable paths.

Environmental impact and resource use of alternative protein sources and meat substitutes

Tuesday, 4th July - 09:50: Special Session: Alternative Proteins and Cellular Agriculture (C1.31 KOG)

Sergiy Smetana [1]

1. *German Institute of Food Technologies (DIL e.V.)*

The modern food system is characterized by high environmental impact, often associated with increased rates of animal production and overconsumption. The adoption of alternative protein sources (to animal products) has the potential to lower the environmental impact. At the same time, there is a risk of the rebound effects associated with increased levels of consumption. The study relied on available data on the environmental impact and resource consumption of alternative sources of food, aimed to replace current products derived from livestock farming. It is concluded that meat substitution could reduce the environmental impact of food system. However, in some cases impacts of alternative sources (e.g., microalgae, insects, purified protein fractions) can have the same level of impact as chicken meat. Higher levels of processing, aimed to increase concentration and purification of resulting fractions, are normally increasing the environmental impact and prices of alternative protein products. Thus, processed plant-based meat substitutes had 1.6-7 times higher environmental impact than less processed sources (e.g., tofu, pulses, and peas). At the same time, extended processing associated with incorporation of water in the product (e.g., high moisture extrusion) results in products with reduced environmental impact (per 1 kg of consumable product) and improved consumer attitude. Hybridization of alternative proteins could be a viable strategy to improve the processability (texture formation, taste improvement) and environmental impact of protein sources. Based on protein comparisons, the impact ranges from most to least can be drawn by grouping foods into three groups: (1) beef, microalgae, cell meat, mycoprotein; (2) poultry meat, insects; (3) plants and plant derivatives. Mycoprotein, microalgae, insects and meat cultures are demonstrating a positive development tendency.

Special Session: Tipping points towards sustainability: what role can industrial ecology play?

Analyzing Tipping Points in Socio-Ecological Technical Systems

Tuesday, 4th July - 09:00: Special Session: Tipping points towards sustainability: what role can industrial ecology play? (B0.13 KOG)

Claudia R. Binder [1], ***Aristide Athanassiadis*** [1], ***Maria Anna Hecher*** [1]

1. HERUS Lab, EPFL

The current climate and energy crises have shown that we need tools for early recognizing tipping points (TPs) in socio-ecological-technical systems (SETS). TPs are defined as “the point where a small intervention leads to a large and long-term consequence for the evolution of a complex system, profoundly altering its mode of operation.” Scholars distinguish between negative and positive TPs. Negative TPs relate to undesired changes that could or should be prevented, e.g., surpassing planetary boundaries, and positive tipping points are framed as desirable and intentional, and often relate to sustainability transitions.
TPs have been mostly analyzed in ecological systems. However, in more complex systems, such as SETS, there is a lack of a framework to understand and potentially anticipate or even shape TPs. Thus, the open question is: how can we characterize and analyze TPs in SETS? We present a framework for doing so. The framework disentangles each of the three sub-systems (namely environmental, technological and social) and presents questions for analyzing the relationships within and among each of them. Thereby we consider also different, related scales, as are (inter-)national, institutional, and individual or global, regional, and local.
Finally, we apply the framework and show first results for three distinct case studies at different spatial and temporal scales: first the case of the energy transition in Paris (200years), Second, the case of a regional energy transition in Austria with a temporal scale of 20 years. Third, the phosphorous transition at the country level in Switzerland and a temporal scale of 40 years. Our findings show some generalities for all cases. TPs in the different subsystems are diachronic, that is, the TPs are interrelated but do not occur simultaneously., i.e., We find that there is a sequence of TPs initiated through a TP in one system, e.g., resources scarcity, health issues, and environmental problems, which leads to TPs in the other subsystems. We discuss the implications of this finding for research in industrial ecology and propose future pathways for including TPs in IE scholarship.

Biophysical Economic Interpretation of the Great Depression: A Critical Episode of an Energy Transition

Tuesday, 4th July - 09:15: Special Session: Tipping points towards sustainability: what role can industrial ecology play? (B0.13 KOG)

Chris Kennedy [1]

1. *University of Victoria*

The Great Depression was a painful episode in the socio-technological transition from a coal/railroad regime to one based on hydrocarbons, motor vehicles and electricity. The Depression principally centred on a change from railroads to motor-vehicle based transportation, but was long and drawn-out due to the hegemonic power that the railroads held over the US economy. The late 1920s saw increased use of hydrocarbon-based technologies, encouraged by discovery of large oil deposits in the US, but the emerging technologies were still reliant on the old technological system. Here I use methods of biophysical economics, mapping energy flows to capital formation, to show the critical role of railroads in the Depression. When the Depression started in 1929, railroads accounted for 24% of the non-residential capital stock; they delivered between 70% and 76% of energy needs; and 69% of energy required for capital formation. Thus a hypothesis emerges that dwindling investment in the railroads beginning in the 1920s and worsening in the 1930s was a major constraint on the economy. In biophysical terms, the US economy's main energy delivery system – coal carried by railcars – was hamstrung. Energy flow Sankey diagrams for 1929 and 1939 show the gradual change in energy systems that occurred over the Depression.

Fundamentals and challenges of modeling bifurcation and catastrophic transition dynamics in socio-ecological technical systems

Tuesday, 4th July - 09:30: Special Session: Tipping points towards sustainability: what role can industrial ecology play? (B0.13 KOG)

David Bristow [1]

1. *University of Victoria*

Bifurcations and catastrophes represent two different but interrelated types of characteristics that can appear as major transitions in the dynamics of complex systems. Bifurcations can lead to different realizable system states. Catastrophic transitions are jumps between state. It is catastrophic transitions that are difficult to undo, and sometimes effectively irreversible. That both types of dynamics are possible in socio-ecological technical systems is well documented, but their study is complicated by modeling uncertainties and data limitations. By using example cases this work illustrates the challenges and benefits in understanding complex dynamics of such systems. In doing so the foundational mathematics are introduced as is progress in data-driven (i.e., machine learning) based approaches. The limitations of these approaches are discussed as are implications for further study and decision making in socio-ecological technical system dynamics.

Critical Raw Materials 2 (short presentations)

Toward China's carbon neutrality: critical rare earth elements supply and demand

Tuesday, 4th July - 12:00: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

Shijiang Xiao [1]

1. *Shanghai Jiao Tong University*

An ambitious goal of carbon neutrality by 2060 had been raised by Chinese central government. To achieve this goal, numerous clean energy infrastructures and electric vehicles will be deployed in China. In this process, the demand for critical rare earth elements (REEs), such as Neodymium (Nd), Praseodymium (Pr), and Dysprosium (Dy), which used in the permanent magnet as irreplaceable components in wind turbines, electric vehicles, and other energy-saving household appliances, will be roaring significantly. However, the specific amounts of supply and demand for these critical REEs within various portfolios of technologies and planning are unclear for both scholars and policy makers. Therefore, this study employs dynamic material flow analysis (MFA) and scenario analysis to forecast the supply and demand for Nd, Pr, and Dy in the process of achieving China's carbon neutrality until 2060. In the supply side, three vital factors have been considered, including primary mining amount, international trade, and recovery level. Similarly, material efficiency, component substitution, and extended lifespan, have been taken into account in the demand side. The results demonstrate that the demand for Nd, Pr, and Dy will reach to 41 kilotons(kt), 10 kt and 8 kt, with increasing 3-fold, 3-fold, and 4-fold in 2060, respectively, if no actions taken in the process of achieving carbon neutrality. The most significant factor to decrease critical REEs demand is increasing REEs material efficiency, which generating 35% declining compared with the demand in business-as-usual. A remarkable decline (66%) in 2060 will be generated if three measures haven been simulated simultaneously. As for the supply side, the total supply for Nd, Pr, and Dy will be 87 kt, 11 kt, and 4 kt in 2060, respectively, if the primary mining growth rate is 5%. The high recovery level will paly a positive role in increasing supply in the long term. From the supply and demand perspective, a single measure will not make any effort for sustainable critical REEs supply for achieving China's carbon neutrality. Finally, three policy implications, including increasing primary mining, technologies advancement, and improving recovery level, have been raised to supply steadily for policy makers.

A dynamic analysis of Rare Earth Elements in the UK electric vehicle stock

Tuesday, 4th July - 12:07: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

Wan-Ting Hsu [1], ***Evi Petavratzi*** [1]

1. British Geological Survey

The transport sector, representing the largest carbon-emitter, contributes to approximately 30% of the UK carbon emissions, with most of them originating from passenger cars (UK Department for Business, Energy & Industrial Strategy, 2022). The transition to electric vehicles (EVs) is critical to meet the UK Net Zero targets by 2050, including the UK Government commitment to end the sale of new petrol and diesel vehicles by 2030, and for all new cars and vans to be fully zero emission by 2035. Achieving these targets would require access to significant quantities of rare earth elements (REE), essential for the manufacture of EV components, such as electric powertrains, electronics and other. Currently, close to 100% of the REE is imported, primarily from China and therefore the associated supply risk to the UK low-carbon transition is considerable. However, the development of a circular economy for REE could provide supply diversification and security of supply for the UK. To understand the potential of the circular economy in the UK decarbonisation agenda, it is necessary to quantify the REE stocks and flows, and understand their evolution. The Met4Tech project aims to address two research questions: 1) How large are in-use stocks of targeted REE, namely neodymium (Nd), dysprosium (Dy), praseodymium (Pr), terbium (Tb), embedded in EVs in the UK? ; 2) What quantities of REE (Nd, Dy, Pr, Tb) could the UK End-of-Life EVs supply up to 2050?

This study applied a retrospective and prospective dynamic material flow analysis to estimate the annual UK end-of-life flows of REE in different EV powertrain vehicles (Battery Electric Vehicles, Plug-in Hybrid Electric Vehicles, and Hybrid Electric Vehicles) between 2014 and 2050. The historical in-use stock data were collated from vehicle licensing statistics and The Society of Motor Manufacturers and Traders. Three scenarios (Leading the Way, Consumer Transformation, and System Transformation) from the National Grid Future Energy Scenarios were used to estimate the prospective in-use stocks of REE embedded in EVs. The mass of different EV powertrain vehicles and material intensity data for Nd, Dy, Pr, Tb were collected through a desk-based review and stakeholder engagement. Material intensities were assumed to remain constant across the temporal scale of the system. Probability densities of EV lifetime distribution with the normal distribution function were applied to estimate the REE end-of-life flows.

Results show that Battery Electric Vehicles (22.5 kilotonnes of Nd, 5.4 kilotonnes of Dy, 0.8 kilotonnes of Tb) and Hybrid Electric Vehicles (3 kilotonnes of Pr) in the System Transformation scenario have the highest in-use stocks of REE in 2050. All scenarios reveal that inflows of REE will continue to increase until 2030. REE will remain in EVs in-use in the short term (e.g. 2030) with only small quantities reaching the end-of-life. However, end-of-life REE flows will increase sharply in the mid to long term, which signifies the potential of secondary supply. Our analysis suggests that UK government collaboration with industry to facilitate the development of a circular ecosystem, as well as investment in scaling up recycling technologies and infrastructure could be highly beneficial for the UK REE supply.

Tracking the Global Anthropogenic Gallium Cycle during 2000-2020: a Trade-Linked Multiregional Material Flow Analysis

Tuesday, 4th July - 12:14: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

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1. *Shanghai Jiao Tong University*

Gallium (Ga) is labelled as a critical metal due to rapid consumption growth, extensive usage in electronic applications (i.e., integrated circuits (ICs), light-emitting diodes (LEDs)), low carbon technologies (i.e., photovoltaic (PV) generation panels) and limited availability as a minor byproduct metal of other metals (mainly from aluminum). Uncovering the global and regional Ga stocks and flows would thus be significant for improving resource efficiency and mitigating potential supply risks. In this study, a trade-linked multiregional material flow analysis (MFA) was applied to map the global and regional Ga cycles from 2000-2020 by combining the statistics data and technical parameters. The results show that approximately 79% of Ga (12164 t) from bauxite mining globally ended up in red mud or entered the aluminum cycle as an impurity, which indicates a great recycling potential of extraction process. Different regions showed different but complementary roles in global Ga supply chains. China played an increasing important role as raw material (Ga metal) supplier during the study period, accounting for 97% of primary Ga production in 2020. Japan and the United States exhibited advantages of high-purity Ga metal refining and electronic devices fabrication. Besides, a total of 2476 ton of Ga was lost during the fabrication process. Among the end uses, neodymium iron boron (NdFeB) permanent magnets accounted for the largest part (36%) of Ga in-use stock globally, followed by LEDs (33%), ICs (23%), photovoltaics (5%) and other uses (2%). The end-of-life Ga flows increased significantly, reached 579 t in 2020. However, no end-of-life recycling is known to occur on both global and regional level due to low concentrations in all major applications. With anticipated increase of Ga demands in LEDs, PVs and magnets, and uncertainty rate of primary production of carrier metals, more joint efforts among different regions and increased recycling are required for ensuring both regional and global Ga supply in the future.

Towards Circularity for Copper: An Analysis of Regional Characteristics and Challenges from a Global Point of View

Tuesday, 4th July - 12:21: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

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1. *Fraunhofer Institute for System and Innovation Research ISI*

Resource use has been and still is growing quickly. It more than tripled over the last fifty years and is expected to more than double until 2060. In light of the pressing issues of climate change biodiversity loss, the need for changes is undeniable. We need a system transformation from the linear "extract, process, use, discard" mentality towards creation of resource cycles in a circular economy. Working towards circularity demands a high level of understanding and quantification for a globalized, complex network of anthropogenic resource use. Industrial ecology aims to provide a data-driven foundation to this process by using, among others, material flow analysis (MFA) to follow resource flows through lifecycle stages, applications, industrial processes, geographical or economical systems and time.

With its high electrical and thermal conductivity, copper is in the centre of our basic infrastructure. Currently the third largest metal by demand, copper demand will grow further with the switch towards renewable energy, continuing electrification and digitalization but also the catch-up of developing countries. Furthermore, copper is a carrier metal for a number of other materials, e.g. precious metals. Therefore, understanding of the anthropogenic use cycle of copper, analyzing the current level of circularity, realizing trends and connectivities and knowing the starting points to unlock further potential for circularity and material efficiency is essential.

At Fraunhofer ISI, we research the copper cycle and its stocks and flows since 2011. In the process, a global and five regional dynamic MFA models were created and numerous focus studies on aspects such as trade flows, recycling technology or future scenarios for copper recycling were conducted [1,2]. Now, we want to present overarching results from our long-term observation. Five models describing the development of copper stocks and flows between 1990 and 2018 in China, the European Union, Japan, Latin America and North America built the foundation. We analyzed the dynamics of copper entering, currently in and leaving the use phase as the use structure and the potential for recycling. We quantified secondary sourcing including international scrap trade, and recycling flows. We summarized the relation of recycling potential, recycling practice and overall copper use providing recycling indicators.

Our comparative MFA approach showed that regions and their copper flows from mining to metal and manufacturing, through the use phase towards waste management and recycling are interdependent within a global network. However, they show different strength and weaknesses, developments and challenges. The responsibility for change towards sustainability and circularity has to be embraced and turned into individual efforts locally, while impact evaluation demands also the global system perspective. MFA helps to provide the necessary understanding and suggestions for both levels. On the highest level of observation, two major challenges can be summarized: Copper demand is expected to rise significantly in coming decades. Even optimal recycling strategies will not be able to sustain demand. Striving for responsible mining will therefore be indispensable. However, we show that there is a significant and during the last decade even increasing gap between recycling potential and practice. Closing this gap and maximizing copper recycling in a socially responsible way while remaining environmentally sensible will be the second major challenge for the future.

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Battery mineral demands and recycling potentials from electric vehicles under 1.5-degree compatible scenario: an Australian case

Tuesday, 4th July - 12:28: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

Haiwei Zhou [1], ***Wen Li*** [2], ***Prakash Singh*** [2]

***1.** The University of Melbourne, **2.** The Univeristy of Melbourne*

Electric vehicle (EV) battery material recycling has received increasing attention in recent years because of the supply risks and associated environmental impacts of primary production. Previous studies investigated EV battery recycling potential in major markets, such as China, Europe, and USA. However, most previous studies often neglected the impacts of different EV fleet development pathways. Although the world expects 100% BEV sales in the long term, the 1.5-degree target demands higher penetration rates of EVs in the short and mid-term, significantly affecting EV battery mineral demand and its recycling potential in the next decades. In addition, research has yet to be conducted in resourceful countries with relatively small markets, such as Australia. The materials contained in the in-use stock and end-of-life (EoL) streams in these countries could be dwarfed by primary production, undermining the attractiveness of domestic battery recycling.

In this study, we estimated the battery mineral demand and recycling potentials of light-duty vehicles (LDVs) in Australia during 2020-2050 for six minerals, namely lithium (Li), cobalt (Co), nickel (Ni), manganese (Mn), graphite, and copper (Cu) using a dynamic material flow analysis model. We built two EV uptake scenarios, namely 1) the business-as-usual (BAU) scenario and 2) the net zero emission (NZE) scenario aligned with the global 1.5-degree target to study the impacts of an accelerated transition toward EVs. We also developed three scenarios where NMC chemistry, LFP chemistry and all-solid-state-battery (ASSB) will dominate the future EV battery market, respectively, to reflect uncertainties concerning battery technology development pathways.

The results show that EV sales in Australia will increase from 6.9K to 2.5M (i.e., a factor of 365) during 2020-2050. As a result, the associated material demand will need to increase at least by factors of 470 for Li, 420 for Ni, 190 for Co, 140 for Mn, 580 for Cu and 420 for graphite during the same period. A 1.5-degree compatible scenario for EV industry could require more battery minerals in the next decades. Specifically, the NZE scenario requires 5.4 million (11.9%) more EVs and 12.6-20.7% more materials cumulatively than the BAU scenario during 2020-2050. A strong breakthrough in advanced battery technology could reduce 18.4-29.6% of the cumulative material demand. Cumulative EV battery material demand until 2050 will be less than one-tenth of current known national reserves, except for Co (14.5-26.9%) and graphite (28.9-45.2%).

EoL batteries could serve as a valuable mineral resource in the long term, even in resourceful countries like Australia. The in-use EV stock in 2050 could contain Co and graphite equivalent to 10.4-18.0% and 20.6-38.6% of the current known national reserve, respectively. Materials contained in EoL batteries could reach up to 43.6-148.5% of the annual demand in 2050 for different minerals, although they will still be negligible in 2030 (only 0.5-1.2% of the annual demand), indicating limited attractiveness of recycling in the short and mid-term. Stronger policy incentives are needed to develop Australia’s domestic EV battery recycling industry.

Critical raw materials demand for green & digital pathways in Spain

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

Martin Lallana [1]***, Jorge Torrubia*** [1]***, Alicia Valero*** [2]

1. CIRCE Institute – University of Zaragoza, 2. CIRCE Institute – Universidad de Zaragoza, Spain

A low-carbon economy is a material-intensive economy. Consequently, the mineral and material dimension of the energy and digital transition has received increasing interest in recent years . At the European level, concerns about the security of supply chains and the economic importance of different materials have led to the development of a list of critical raw materials since 2011. This list, updated every three years, has been growing steadily. And it is expected to continue as the demand for more quantity and variety of raw materials for the energy and digital transition increases. By 2020, it already accounted for 30 minerals and groups of minerals. This situation has driven policy changes in the European Union, such as the support for onshoring mining within member states (European Commission, 2020). However, the adaptation of these strategic plans to the Spanish framework has not been accompanied by a specific study of future mineral demand. This opens an important gap that needs to be filled. At the same time, Europe leads the Waste Electrical and Electronic Equipment (WEEE) generation per capita worldwide. Spain generated 19 kg per capita in 2019, far from the 2.4 or 7.2 generated by emerging powers such as India and China respectively (Forti et al., 2020). Despite this promising supply potential, there is hardly any specific study of the possible recovery of secondary raw materials from this high-value technological waste.

Therefore, our analysis sets out two main objectives for the specific case of Spain. First, we perform a detailed estimation of the future mineral demand associated with the energy and digital transition according to the already approved strategic plans and public policies. To this end, we work on government energy transition documents with a 2030 and 2050 horizon, as well as on strategic plans for energy storage and on strategic projects for economic recovery and transformation associated with the Next Generation EU funds. By applying a series of assumptions on the technologies used, material intensity and recycling rates, we obtain an estimate of future mineral demand for the specific case of Spain up to 2050.

Secondly, we make an approximation of the amount of secondary raw materials that could be recovered from the collection and recycling of WEEE. For this purpose, we apply a highly disaggregated analysis working with data from 43 categories of EEE placed on the market, following the UNU-Keys classification and considering a distribution of lifetimes. In previous research, the results showed the enormous opportunities for urban mining in Spain: the EEE placed on the market between 2016 and 2021 contains 1.4 million tonnes of metals, of which 20,000 tons are critical metals (Torrubia et al., 2023). Through this analysis, we project these results to a time horizon of 2050, based on certain assumptions regarding the degree of digitalisation, the WEEE collection capacity, and the degree of efficiency in recycling the raw materials contained in them.

Through these two calculations, we approach a specific picture of the mineral implications of the energy and digital transition currently at the center of public policy making. From the results obtained, we conclude with some recommendations for policy makers to ensure maximum sustainability and achieve a more circular economy that minimizes waste and secures the supply of critical raw materials.

Upcycling & Recycling (short presentations)

Transforming landfill to a relative carbon-negative sector by mining its overlooked carbon stock

Tuesday, 4th July - 12:00: Upcycling & Recycling (short presentations) (C1.31 KOG)

Shijun Ma [1]***, Chuanbin Zhou*** [2]

***1.** University College London,* ***2.** RCEES*

Decomposition of landfilled organic carbon stock accounted for 2% of global greenhouse gas (GHG) emissions in 2016. If current waste management remain unchanged, both organic carbon input and GHG emissions in landfills will double by 2050. The most effective approach to GHG emission mitigation for landfills is to reduce landfilled organic carbon stock by limiting waste input or through mining. However, no studies have addressed the trade-off of these mitigation strategies and climate change mitigation potential of landfills. Here we introduce a quantitative-based solid-water-gas coupling transformation model to estimate organic carbon stock of landfills in China. And co-benefits of GHG emission mitigation from different stock-reduction-based interventions are explored. Results show that during 2001-2020, Nearly 93% of organic carbon input was stored in landfills in China (503.3±4.2Tg). Mining and utilizing these carbon stock would offset 20% of soil organic carbon of urban green space and more than six years of residential electricity consumption, thus creating huge economic value. Moreover, under the dual effects of landfilling rate decrease and stock mining, the organic carbon stock of landfills would be greatly reduced to 229.1Tg by 2030, with an annual relative methane emission of -62.0Tg CO_2eq. Meanwhile, the cumulative relative GHG emission reduction of 836.2Tg can be also achieved, accounting for 1.1%-3.6% and 1.2%-8.7% of the GHG emission debt for China to achieve 1.5℃ and 2℃ warming targets. Landfill can be a relative carbon-negative sector by adopting multiple policy-interventions, showing its great potential in contribution to the carbon-neutral society in the future.

Materials Catalogue for Novel and Responsive Materials

Tuesday, 4th July - 12:07: Upcycling & Recycling (short presentations) (C1.31 KOG)

Layla van Ellen [1]***, Ben Bridgens*** [1]***, Oliver Heidrich*** [2]

1. *Hub for Biotechnology in the Built Environment, Newcastle University, NE1 7RU, Newcastle-Upon-Tyne, UK,* ***2.*** *School of Engineering, Newcastle University, Newcastle Upon Tyne, NE1 7RU, United Kingdom*

The built environment is facing many challenges such as increasingly extreme climatic conditions, resource depletion and biodiversity loss[1]. To address these challenges, different adaptability strategies are investigated[2], focusing on novel responsive and dynamic materials. Biomaterials and (engineered) living materials have potential to enable buildings to reversibly respond to changes in their environmental context[3], e.g. changes in temperatures, relative humidity, or light intensity. However, the responsiveness properties of these novel materials are not yet systematically characterized. Even the mechanical and physical properties of some living materials have not yet been studied as the materials are sometimes microscopic, such as bacterial spores.

This work presents the development of a materials catalogue that focusses on novel materials that can be used in the built environment in the future. The responsiveness of novel biomaterials and (engineered) living materials are characterised and assessed in a matrix. The presentation will show which indicators are chosen for material responsiveness (e.g. response types, frequency, speed, reversibility) and for the related stimuli. Then, novel living materials such as bacterial cellulose, microbial spores, and mycelium are benchmarked against bulk materials used as scaffolds for biomaterials, and in particular living materials, such as natural fibre textiles, concrete and wood. The data is compiled in nine materials factsheets that form the catalogue.

Finally, the potential applications in the built environment are mapped alongside the maturity of the development of the materials (i.e. the technology readiness level) and the scales at which the materials have been developed (from nano to macro). The materials are mapped using the bespoke *Scale Tool*, which shows barriers to implementation in construction and also potential for use as responsive materials for adaptable buildings. For example, bacterial cellulose is represented spanning many sizes and technology readiness levels on the *Scale Tool*, which is a material researched for its potential tensile strength[4] but also as scaffold to host biological elements and information[5,6]. The map suggests that combining two or more biological materials together into hybrid (living) materials has potential to tackle one of the biggest challenges in using novel responsive biomaterials in the built environment: scaling-up.

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Leveraging Drone Technology and Data Analysis Techniques to Transform Illegal Waste Sites into Valuable Resources: An Exploratory Study

Tuesday, 4th July - 12:14: Upcycling & Recycling (short presentations) (C1.31 KOG)

Adi Mager [1], ***Vered Blass*** [2]

1. *Tel Aviv University,* ***2.*** *Tel-Aviv University*

In light of the ongoing concern over the exploitation and potential shortage of Earth's natural resources, this study aimed to investigate the feasibility of transforming illegal waste sites into valuable resources. We used a multi-disciplinary approach combining drone technology, spatial mapping, geographic information systems (GIS), image processing, and life cycle assessment (LCA) data. We present data from pilots that were conducted in Israel since 2019 and include materials classification, economic data, environmental impacts assessment, and the connection to the relevant SDGs. We then present a national scale assessment of the economic potential of our approach.

The integration of aerial mapping and economic/environmental analysis methodologies highlights the importance of technology in promoting a local circular economy and creating a more sustainable future. Our work outcome can provide missing data that the state, local authorities, contractors, and companies that monitor and manage waste and recycled raw materials may find useful.

Ex-ante LCA of new magnet recycling technology

Tuesday, 4th July - 12:21: Upcycling & Recycling (short presentations) (C1.31 KOG)

Sander van Nielen [1], ***Brenda Miranda Xicotencatl*** [1], ***René Kleijn*** [1]
1. *Leiden University, CML*

The rare earth magnet market experiences serious turmoil: prices fluctuate heavily while the demand is growing exponentially driven by wind turbines and electric vehicles. Recycling helps to reduce the pressure on rare earth mining, while presenting a solution for growing waste flows. While the development of recycling technologies is ongoing, we investigate the further development of short-loop recycling from small scale to industrial scale. This ex-ante LCA study combines input from expert technology forecasts, thermodynamic modelling, manufacturer data for equipment, and energy scenarios. Our approach systematically considers all mechanisms for performance changes when upscaling, from size scaling to decarbonizing electricity. The results show the effect of process design choices and the effect of end-of-life product inputs. Moreover, the assessment of multiple process improvements leads to an outlook of potential development pathways towards low-emission magnet recycling. Our systematic approach, which involves the active participation of technology developers, can be extended to support the upscaling of other emergent technologies.

Prediction of China's municipal solid waste generation and carbon neutrality potential under the shared socioeconomic pathways

Tuesday, 4th July - 12:28: Upcycling & Recycling (short presentations) (C1.31 KOG)

Huijuan Dong [1]

1. *Shanghai Jiao Tong University*

With fast urbanization and industrialization, China faces great challenge of municipal solid waste (MSW) treatment due to fast increase of MSW generation. Furthermore, as the largest CO_2 emitter, China also faces great challenge of greenhouse gas (GHG) emission reduction and achieving carbon neutrality by year 2060. Thus, it is crucial to mitigate greenhouse gas (GHG) emissions from MSW sector and forecast the carbon neutrality potential of MSW treatment sector, one of the main anthropogenic sources for GHG mitigation. However, such study is still missing. To fill such a research gap, this study develops MSW generation forecast models for more precise MSW projection using machine learning method. Then GHG emissions from MSW treatment by combining IPCC and logarithmic mean divisia index methods are further developed. Carbon neutrality potentials of China towards 2060 are analyzed under assumed policy scenarios and shared socioeconomic pathways (SSPs). Results showed that XGBoost model is proved to be effective in MSW forecast. MSW generation of China in 2060 is estimated to be 464 ~ 688 megatons under different SSPs scenarios, about four to six times of that in 2000. GHG emissions from China's MSW treatment increased nearly 40 megatons in the past decade, with incineration emissions increasing fast. Economic development was the dominant and positive driving force of MSW GHG emissions. Scenario analysis revealed that carbon neutrality from MSW treatment could be achieved only after implementing MSW classification, reducing approximately 150 megatons GHG emissions. Fossil-fueled development pathway (SSP5) will generate the most GHG emissions among SSPs. Finally, policy recommendations on priority regions, MSW treatment transition and circular economy schemes are proposed.

This novelty of this study is that not only a machine learning based method to accurately forecast MSW generation is established, but also MSW treatment and SSPs pathways are innovatively combined to forecast the carbon neutrality potential of MSW treatment sector.

Mitigation Policies (short presentations)

Towards a comprehensive and inclusive European Carbon Border Adjustment Mechanism

Tuesday, 4th July - 12:00: Mitigation Policies (short presentations) (A1.44 KOG)

Timothé Beaufils [1], Hauke Ward [2], Michael Jakob [3], Leonie Wenz [1]

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The European Union (EU) will implement a Carbon Border Adjustment Mechanism (CBAM) to reach its climate mitigation targets while avoiding carbon leakage. Under an EU CBAM regime, emissions caused by goods imported to the EU would be taxed based on the emissions their production generated elsewhere in the world. The EU CBAM may also entail export rebates, which would deduct the carbon price from the goods exported from the EU. Beyond EU producers and consumers, an EU CBAM would impact industries and final users in third countries through their direct and indirect trade dependence on the EU. Using Multi-Regional Input-Output (MRIO) data and a novel throughflow-based accounting framework, we here explore different options of implementation for the EU CBAM, based on different products and scope coverage. We propose a new approach to explore how an EU CBAM would channel the EU carbon price to third countries and quantify which countries would be the most affected. We find that, despite having few responsibilities in the current climate crisis, some low- and middle-income countries dependent on the EU for their exports would be disproportionally pressured by an EU CBAM, as a large share of their domestic emissions would be covered by the EU carbon price. Finally, we propose avenues to implement an inclusive recycling of the fiscal revenue of the EU CBAM toward vulnerable countries. We show that such recycling scheme could make an EU CBAM more acceptable for the EU trade partners and foster increased climate cooperation, but would require balancing between conflicting interests.

Challenges and opportunities of city-level Scope 3 emission reporting and policies

Tuesday, 4th July - 12:07: Mitigation Policies (short presentations) (A1.44 KOG)

Kaihui Song [1], ***Angel Hsu*** [1]

1. University of North Carolina at Chapel Hill

Cities have been recognized for their great potential in providing accessible, scalable and impactful climate mitigation. Several city-led initiatives have been growing in recent years to unite and push for bolder climate actions at the city scale, including C-40 Cities for Climate Leadership, Local Governments for Sustainability (ICLEI), and the Global Covenant of Mayors for Climate and Energy (CoM) initiatives. However, there remain challenges to tracking and assessing their performance with credible and consistent measures to develop effective climate policies. Major challenges include the lack of accurate emissions accounting and reporting both within cities' jurisdictions and out of boundary emissions embodied in the supply chains (Scope 3 emissions).

Recent studies have made progress in advancing methods to quantify cities' emission impacts and roles in global value chains. A gap exists, however, between these methodological advances and cities' ability to devise effective policies to address these significant, but underestimated Scope 3 emissions. Utilizing self-reported disclosures through CDP, this study reviews the landscape of cities' climate commitments and Scope 3 emissions reporting. We find that, despite the increasing attention to Scope 3 emissions from the international community, only around 2% of cities with climate targets have reported Scope 3 emissions, most of which are located in Europe and North America. To understand the global relevance and context of this Scope 3 reporting gap, we summarize current Scope 3 climate policies, which primarily exist in the US, EU and UK. Finally, we review methodologies and available data to quantify GHG emissions, including Scope 3 emissions, for cities in the US, Australia, China and Japan to make recommendations for better connecting GHG quantification methods to climate policy actions. The synthesis can inform policymakers with actionable steps to accelerate city-level climate mitigation considering their embedded nature in global supply chains.

Theory of Common Conflicts: Conceptualizing emergent ethics based view of social-ecological systems

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:14: Mitigation Policies (short presentations) (A1.44 KOG)

Saurabh Vij [1], Shauhrat Chopra [1]

1. City University of Hong Kong

Convergence of social, economic and environmental issues can be noted across the world. This can be evidenced through acceptability and popularity of goals, such as SDGs across institutes (e.g. in education, markets) and regions at different scales (e.g. cities, states, countries). This scenario, in our view, carries the potential, as evidenced by literature review, of developing into a normative position(i.e. a philosophical outlook of emergent ethics). It enables individual and collective responsible behaviour to ensure social, economic and environmental emergence at system level irrespective of local beliefs, values and religion. Such emergence for pre-defined time periods can be expected at different spatial scales (i.e. local, regional, national, global) for all locations. With such a top-down view, which is rarely considered in the study of socio-ecological systems (SES), how interactions might shape between users and how they can lead to social and ecological outcomes is the focus of our study. We are utilizing Elnor Ostrom's SES framework to conceptualize the proposed scenario, where all agents intend to reduce negative impacts for n-topics. Under this set-up, by utilizing axiomatic methodology, we identify all possible types of conflicts that can exist. The identification of conflicts is informed by the work of K Törnblom in conflict conceptualization. It is found that for the proposed SES conceptual frame (with key variables identified), if the normative position of ensuring social and ecological emergence for n-topics is embraced by all members of society, only a limited number of conflicts can exist. Since, the conflicts are limited only therefore the need of congruence between involved parties becomes also limited and as a result pragmatic possibilities of social-ecological systems modelling from a top-down view are opened up to identify set of possible future pathways for humanity.This fundamentally changes the view about the impossibility (as claimed by many including E. Ostrom) of not being able to realize empirical generalizations of the type of rules required for self-governing regimes located under nested settings. The only assumption made here is an all-inclusive embrace of emergent ethics, a philosophical outlook that does consider local normative priorities to ensure justice is delivered but only along with the contingency of ensuring emergence at system level that is defined with specific spatial and temporal bounds.The application of resulting theory informing about conflicts is demonstrated by showing its application to analyse the global issue of GHG emissions by various countries.

Evaluation of Climate-change Adaptation Measures from the Perspective of Co-benefits with Mitigation - Case Study of Logging Trees in River Channels -

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:21: Mitigation Policies (short presentations) (A1.44 KOG)

Sotaro Takenaka [1]***, Kiyo Kurisu*** [1]***, Kensuke Fukushi*** [1]

1. *The University of Tokyo*

Since there are climate change risks that cannot be prevented by mitigation measures alone, adaptation measures to climate change have become increasingly important. While there is a social demand for adaptation measures that bring co-benefits with mitigation, there are few studies that quantitatively evaluate changes in greenhouse gas (GHG) emissions derived from adaptation measures.
In order to provide an outline of multi-perspective evaluation for adaptation measures including GHG reduction, we picked up the case of cutting down trees in a river channel for flood control. When the logged trees are used as biomass, they could contribute to both mitigation and adaptation.
In Yamagata Prefecture, located in the Tohoku region of Japan, there is a river called the Mogami River with a basin area of 7,040 km2, which has experienced four floods in the last 20 years. Currently, the trees in the Mogami River channel are cut down for flood control and chipped to be used as sources of power and heat. Unlike cutting trees in forests, there are various restrictions on cutting trees in river channels. For example, shrubs interfere with logging, so trees are cut in the winter when the snow flattens the shrubs. There is also the restriction that trees on private property and trees nesting birds cannot be cut. In addition, the size of the tree should be carefully evaluated before cutting, as the size of the diameter determines the profit.
We conducted a Life Cycle Assessment (LCA) to evaluate the mitigation effects of the tree utilizations, such as power and heat. In the target area, cut-down trees are naturally dried and chipped. The logs are used for boilers at three facilities, where the heat generated is used for heating and boiling, replacing heavy oil and light oil. In addition, a part of branches and leaves are used for power generation. The foreground data were collected through field surveys and interviews with business operators. One-ton wet weight of cut-down tree was set as a functional unit. GHG emissions were calculated and the decarbonization benefits of fossil fuel substitution were analyzed. Changes in carbon stocks, absorption by trees, and GHG emissions from construction were not considered. The results showed that the overall GHG emission was -430 kg-CO2eq./t-wet log. The significant reduction in GHG emission was derived by the natural-drying process, shorter transportation due to local biomass use, and no land use change. The monetary value of this GHG-reduction effect was estimated using the carbon price and the purchase price of renewable energy.
We also calculated the annual flood damage before and after the logging and estimated the amount of expected flood-damage reduction. Then, we evaluated the monetary value of adaptation measure alone and the monetary value of the mitigation effect by using logged trees.

Sectoral Coordination Maximizes China's Provincial Building GHG Emission Mitigation

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:28: Mitigation Policies (short presentations) (A1.44 KOG)

Qiance Liu [1]***, Kairui You*** [2]***, Xin Ouyang*** [3]***, Weiguang Cai*** [2]***, Gang Liu*** [1]

1. *University of Southern Denmark,* ***2.*** *Chongqing University,* ***3.*** *University of Chinese Academy of Sciences*

The increasing building stocks and associated material and energy consumption have contributed to one-fifth of global greenhouse gas (GHG) emissions. Achieving climate goals relies on a higher-resolution building GHG emission result to guide local building decarbonization, especially for those large countries like China. As the largest building GHG emission emitter, China is about to reach the "turning point" when the boom of new buildings calms down and the large-scale renovation starts. Therefore, China may face double challenges in its low-carbon building transition efforts in the next decade: the accelerating construction of new buildings for developing countries and the renovation of existing buildings for developed countries.
The recent years have seen an increasing body of literature on building GHG emission modelling and mitigation strategies discussion, including for China. However, how the renovations will impact building decarbonization has not been explicitly presented yet for China. At the same time, few studies considered the regional disparities in operational and embodied GHG emissions associated with Chinese buildings.
Here we aim to address these knowledge gaps by developing a Building-Material-Energy-Emission (BMEE) model that includes a novel renovation module to assess CO_2 emissions and mitigation potentials from buildings in mainland China on the province level from 2000 to 2060. We further developed different scenarios for emission reduction, with the recently released policies from the Chinese government selected as benchmarks.
We show that CO_2 emissions from Chinese buildings are expected to peak the latest by 2026, and up to 61.6 Gt CO_2 can be mitigated in the next forty years. The five dominant strategies (i.e., urban renewal, green building, low-carbon construction, circular economy, and energy transition) will make significant but various contributions to China's national and provincial building decarbonization under the current policy options. More comprehensive and deep building decarbonization strategies, particularly, need coordination from all related sectors. Our results could provide concrete and accurate implications in guiding Chinese buildings' GHG emission mitigation and call for more attention to the upcoming "Renovation Wave" in China and the world in the post-pandemic age.

Urban IE (short presentations)

Analysis of Urban GHG Mitigation progress - a Case Study of UK Local Authorities

Tuesday, 4th July - 12:00: Urban IE (short presentations) (B0.17 KOG)

Eugene Mohareb [1]***, Thomas Butt*** [1]***, Kelvin Egbor*** [1]***, Arman Hashemi*** [2]***, Oliver Heidrich*** [3]

1. *University of Reading,* ***2.*** *University of East London,* ***3.*** *Newcastle University*

Countries and their constituent urban areas are striving to achieve dramatic greenhouse gas (GHG) emissions reductions under the current net-zero agenda. The UK has set policy to reduce emissions, establishing the Climate Change Act (2008) and its recent amendment to achieve net-zero by 2050. In response to recent IPCC (2019) report on the consequences of missing the target of limiting average global temperature 1.5°C, the majority of UK local governments set accelerated timelines to achieving net-zero. Many of these local authorities have aimed to achieve net-zero as early as 2030. Given the history of the UK and its subnational governments' initiatives to mitigate GHGs, it is worthwhile to take stock of achievements to date at the local authority level to understand drivers of success, barriers to reduction so far, and the challenges that remain towards net-zero.

This research reviews the progress of 378 local authorities across the UK in mitigating GHG emissions between 2005 and 2020. Regression analyses are applied between local authorities' GHG emission reductions and selected explanatory variables identified from the literature to explore mitigation performance over time (including population density, household income, and manufacturing employment). Subsector reductions from waste, domestic buildings, industrial & commercial sites, and transportation are assessed to determine influences of explanatory variables on each local authority's emission reduction performance.
Substantial and relatively consistent GHG emissions reductions were achieved in this time frame, with average total reductions across UK local authorities of nearly 50%. Population density was moderately-to-strongly correlated with the success of transportation GHG emissions mitigation, though this sector has seen the smallest percentage declines over this period. Local authorities with densities below 25 inhabitants per hectare were generally among the poorest performers in transportation GHG mitigation. This underscores the need to support remote working and electrification of personal transportation in areas where public/active transportation options are not viable alternatives. Furthermore, consideration of population density in conjunction with domestic and urban planning will allow for future emissions reductions to occur across the UK. Fundamentally, GHG emissions reductions to date are largely driven by historic factors (density), shifting economic structures (deindustrialisation), and centralised initiatives (decarbonisation of electricity generation).

Bottom-up characterization of the urban metabolism of reusing electric vehicle batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:07: Urban IE (short presentations) (B0.17 KOG)

Mateo Sanclemente Crespo [1], ***Laura Talens Peiró*** [1], ***Xavier Gabarrell i Durany*** [1]

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Two objectives converge at the reuse of electric vehicle batteries for stationary energy storage: renewable energy intermittence management and reduction in environmental impacts for battery fabrication. The study of the environmental benefits and impacts of reusing EV batteries has been focused on two main aspects by two main methodologies. First, single battery scale Life Cycle case studies proposing the avoidance of a new battery have focused on CO saving and, second, regional and global scale studies employing Material Flow Analysis to quantify the mineral extraction required under different scenarios. In this study, we aimed at advancing in the assessment of greenhouse gas emissions and mineral savings of reusing EV batteries by inferring their potential incorporation and targeted use in a local scale study. Supported by a series of four household surveys, of above 1,000 respondents each, on dwelling typology and family time use, we studied the urban metabolism of a medium sized city in the metropolitan area of Barcelona, with broad household inequality, diversity of dwelling typologies, and abundance of industrial and service facilities. The study of the current status shows that both the dwelling typology and the inhabitants typology are determining factors in the household's tools for adaptation to increasing energy prices and increasing prices volatility, presenting high contrast in technological solutions versus social adaptation. From the characterization of current household patterns, we provided EV batteries' end-of-life and reuse scenarios, proposing the metabolic patterns required and derived of such scenarios in the urban context. In line with previous studies, we found that the GHG emissions savings derived from the use of batteries for household purposes could turn negative depending on the household typology and the status of the electricity market. Additionally, the increase in battery reuse flows will be abrupt and may not avoid the need for upcoming intense mineral extraction if EV sales targets are met. Lastly, from scenarios based on the current policy and administrative patterns, we found an increase in inequality for the access of energy. These results suggest a need to revise current policies to align with the claimed purposes of battery reutilization.

Beyond greenhouse gases – staying within planetary boundaries in urban and regional Australia

Tuesday, 4th July - 12:14: Urban IE (short presentations) (B0.17 KOG)

Kylie Goodwin [1], ***Thomas Wiedmann*** [1], ***Mengyu Li*** [2]

1. *UNSW Sydney,* ***2.*** *The University of Sydney*

In 2022 Australians made a clear expression of environmental concern, voting in a new government and many independents with strong environmental policies, highlighting a clear shift in public sentiment after many years of heated debate. Australia has now ramped up environmental ambition and committed to higher emissions reduction targets and biodiversity goals. It is rapidly expanding renewable electricity generation, with unprecedented investment in new technologies. But what about the other planetary boundaries? And how does Australia's consumption measure up?

Our new research aims to envisage what a sustainable Australia beyond greenhouse gases would mean across different categories of consumption in Australia. This research utilises recently developed nested environmentally-extended MRIO capability to map footprints across the full global supply chain for 12 different indicators representing all planetary boundaries excluding ozone layer, plus materials and energy use and employment, comparing capital city and regional areas within Australia. We identify critical intervention points for impact reduction, and further identify key areas of environmental concern for different types of consumption.

A UM-LCA framework to estimate environmental impacts of regional and urban areas

Tuesday, 4th July - 12:21: Urban IE (short presentations) (B0.17 KOG)

Joana Bastos [1]***, Riccardo Fraboni*** [2]***, Rita Garcia*** [3]***, Leonardo Rosado*** [4]

1. *European Commission, Joint Research Centre (JRC), Directorate for Energy, Mobility and Climate, Clean Air and Climate Unit; Institute for Renewable Energy, Eurac Research,* ***2.*** *Institute for Renewable Energy, Eurac Research,* ***3.*** *Itecons – Institute for Research and Technological Development in Construction, Energy, Environment and Sustainability,* ***4.*** *Chalmers University of Technology*

Policies and strategies to improve environmental sustainability in cities and regions have often focused on a single or on a limited number of sectors and/or subsystems, which may offer limited potential to significantly reduce the overall impacts associated with a geographic area. Integrated environmental impact assessment frameworks at region/city level that can capture the complexity of cities and their inter-linked sub-systems are needed to identify sectors associated with environmental hotspots and/or significant improvement potential, and to support effective decision-making toward environmentally sustainable urban and regional development. Such frameworks should be holistic, consider a wide range of environmental impacts, and have a life-cycle perspective. This paper provides a systematic and comprehensive framework to calculate the potential life-cycle environmental impacts of consumption associated with regional and urban areas. We couple urban metabolism (UM) with life-cycle assessment (LCA), to estimate the life-cycle environmental impacts of the Autonomous Province of Trento, in Northern Italy, and of its capital city, Trento, in 2019. Trento is a medium-sized city, a size that is representative of a large part of the EU's urban fabric.

The proposed framework draws on the UM-LCA methodology applied in Lavers Westin et al. (2019), which estimated environmental impacts of urban consumption with a cradle-to-gate approach, and extends it to assess cradle-to-grave impacts. First, we developed a material flow accounting (MFA) model to estimate annual domestic material consumption in the region and city, for thousands of product types, organized into combined nomenclature (CN) product categories. Second, we selected representative product types, based on three criteria: (i) consumption share in terms of mass, overall and within the product category; (ii) comparability of environmental impacts among product types with large mass shares in the product category; and (iii) product types known to have potentially high environmental impacts, based on previous literature. Third, we developed a life-cycle model for the overall regional and urban annual consumption using ecoinvent data, and calculated potential environmental impacts for eight impact categories (selected from the Environmental Footprint package), with a cradle-to-gate approach (incl. extraction of raw materials and production). For a selection of consumption areas, we developed a cradle-to-grave model and compared the results with those using a cradle-to-gate approach, demonstrating the importance of including the use phase, particularly for urban systems and sectors related to transportation, for example, which account for a large share of the overall impacts associated with regional and urban areas.

Reference: Lavers Westin A. et al. (2019) Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. J Clean Prod 226:526–39. doi: 10.1016/j.jclepro.2019.04.036

The spatial dimension of urban metabolism. A design atlas of resource-sensitive urban archetypes.

Tuesday, 4th July - 12:28: Urban IE (short presentations) (B0.17 KOG)

Daniel Otero Peña [1], ***Daniela Perrotti*** [1]

1. Louvain Research Institute for Landscape, Architecture and Built Environment (LAB), University of Louvain, UCLouvain

Urban metabolism (UM) studies provide valuable insights that can improve resource efficiency in cities and have evolved in recent years by adopting an interdisciplinary and multiscale approach of urban systems, paying increasing attention to socioeconomic contexts, relations of power among stakeholders, and the study of ecological dynamics and public health of entire urban areas (Castán Broto, et al., 2012). Localizing and quantifying urban flows and stocks could be of great value for identifying infrastructure deficiencies and unequal resource accessibility for vulnerable population groups (Musango et al., 2020). However, only few studies provide spatially explicit accountings of UM flows. This study combines geographical information system (GIS) and qualitative data collection to provide a combined top-down and bottom-up analytical approach which aims to improve UM application in urban and landscape planning. Building on previous research (Otero Peña et al., 2022), our method integrates finer-scale quantitative and qualitative socio-ecological data into the design of urban public spaces. We test our approach in two case studies, Mexico City and Brussels, two Global South/North city-regions with complex relations with resource flows and vulnerable communities. First, a GIS analysis is presented to highlight (i) resource efficiency hotspots at the city-region scale and (ii) socio-ecological dynamics at the neighborhood scale. Then, we explored the socio-ecological dynamics between a set of ongoing local projects and different stakeholders involved (e.g. community-led resource management projects). Finally, we developed an atlas of urban design archetypes for resource-sensitive public spaces, based on the following three dimensions: spatial characteristics (location, scale, and typology of public spaces), governance (actors involved in each project/design), and socio-ecological dynamics (resource accessibility and community involvement). The research is supported by extensive literature review, collection of primary spatial data and compilation of secondary data (e.g., neighborhood-level resource demand), field visits, and semi-structured interviews with key stakeholders. The results of our multiscale spatially-explicit analysis provide an improved understanding of the metabolic profiles of each urban design archetype, which can leverage a more resource-efficient and context-sensitive design and implementation of open space networks. Furthermore, it revealed the relevance of mapping and 3D modelling to identify and classify various urban design archetypes that, based on their characteristics, can focus on resource harvesting at the plot/site level, promoting community engagement and enhancing the use of public spaces. The findings of this study can inform planning practitioners to formulate and apply landscape infrastructure design strategies based on a context- and community-specific approach to achieve more resource-efficient and resilient cities.

Supply chain Design and Spatial Optimization of Kitchen Waste compost as urban green space Fertilizer: Take Haidian District of Beijing as an example

Tuesday, 4th July - 12:35: Urban IE (short presentations) (B0.17 KOG)

***Ling Han* [1], *Wenrui Shen* [1], *Yilong Xiao* [1], *Xin Tong* [2]**

1. College of Environmental Sciences and Engineering, Peking University, 2. College of Urban and Environmental Sciences, Peking University

At present, the amount of kitchen waste is increasing rapidly. Centralized biochemical treatment is becoming more and more dominant. Due to NIMBY, it is very difficult to expand the treatment capacity. On the other hand, the demand of organic fertilizer for the urban greenbelt is far from being satisfied. The paper tries to carry supply chain optimization research out on the resource utilization of kitchen waste composting as an organic fertilizer and applying in urban green space. Investigate, taking the Haidian District as an example. Firstly, we estimate whether the current centralized processing capacity of the Haidian District can meet the kitchen waste. Secondly, after estimating the spatial distribution of kitchen waste output and green space fertilization demand between residents and non-residents in Haidian District, we optimize the setting of compost bins and the arrangement of employees according to the transport distance of garbage and fertilizer, so as to minimize the economic cost. Finally, the economic and environmental benefits are assessed. We find that when the garbage separation rate of kitchen waste reaches to 66.6%, there would be a 99t gap about the centralized biochemical treatment capacity of Haidian District. According to the optimization results, the distributed aerobic compost can save money every six months compared with the centralized biochemical treatment. 6,006,000 yuan. More than half of the sites in Haidian District can meet the requirements of organic fertilizer application of 0.5kg per square meter every half year. According to the LCA analysis, carbon reduction per t of waste is 6.41kg. We also compare this method with other kitchen waste treatment.

Water 1 (short presentations)

The more wastewater reclamation, the less water stress?

Tuesday, 4th July - 12:00: Water 1 (short presentations) (C0.06 KOG)

Dan Wang [1], ***Reetik-Kumar Sahu*** [2], ***Taher Kahil*** [2], ***Ting Tang*** [2], ***Yuli Shan*** [3], ***Klaus Hubacek*** [4]

1. *Integrated Research on Energy Environment and Society (IREES), Energy Sustainability Research Institute Groningen (ESRIG), University of Groningen,* ***2.*** *International Institute for Applied Systems Analysis,* ***3.*** *University of Birmingham,* ***4.*** *University of Groningen*

Wastewater treatment and reclamation is crucial in reducing water stress, as it is a vital stage in the social water cycle, which involves water quantity and pollutant flows in the processes of withdrawal, loss, consumption, return flows, wastewater reuse as well as flows between regions. It is believed that increasing the rate of wastewater reuse and having more wastewater reclamation can reduce water stress. This study aims to explore whether reusing more wastewater means less water stress in China. To address this problem, our study investigates the effect of reclaimed water reuse on water stress in both water-saving and non-water-saving scenarios across all socio-economic sectors. Specifically, we firstly apply Material Flow Analysis (MFA) to track water quantity and pollutant flows in the societal water cycle across various economic sectors and provinces in China in 2017. Subsequently, based on our dataset developing based on provincial-level Water Resources Bulletin (WRB) and firm-level industrial dataset of the China Environmental Statistics Database (CESD), we obtain strict sectoral water consumption data and then apply it to each province to minimize return flows (return flows to wastewater treatment, and return flows directly discharge to the environment) and water loss and, thus, minimize water withdrawal, while holding water consumption constant. Finally, under the baseline and strict water conservation conditions, we calculate the potential for reclaimed water reuse, assuming 90% of return flows are utilized for wastewater treatment. Our results show that the baseline potential for reclaimed water reuse is between 0.08-6.18 billion m^3, which decreases to 0.02-1.5 billion m^3, under the water-saving scenario. The baseline water quantity and quality stress levels range from 0.01-7.5 and 0.1-19.5, respectively, and drop to 0.006-2.58 and 0-9.9 under the water-saving scenario. The results suggest that higher reclaimed water reuse does not necessarily lead to lower water stress in a region. The potential for wastewater treatment and reuse is dependent on return flows, which can impact water use efficiency and increase water stress. To effectively alleviate water stress, increasing wastewater reuse is important, but water conservation needs to be a priority.

Life Cycle Environmental Impacts of Using Wastewater-derived Products

Tuesday, 4th July - 12:07: Water 1 (short presentations) (C0.06 KOG)

Ka Leung Lam [1]

1. Duke Kunshan University

Resource recovery from wastewater is gaining increasing attention (Kehrein *et al.*, 2019). Recovering phosphorus from wastewater in more concentrated forms has potential to sustainably recirculate phosphorus from cities to agriculture (Harder *et al.*, 2019). Life cycle assessment (LCA) has been used to evaluate the potential environmental impacts of various wastewater-based phosphorus recovery opportunities (Lam *et al.*, 2020). Most LCA studies related to wastewater-based phosphorus recovery used the *process perspective* or the *product perspective* in their assessments. We proposed the use of the *end-user perspective* to understand the life cycle environmental consequences of substituting conventional inputs with recovered products at the end user's product system (Lam *et al.*, 2022).

This study assessed life cycle environmental impacts of substituting half of the conventional phosphorus rock-based fertilizers used in an average U.S. soybean production system with wastewater-derived phosphorus products (i.e., struvite, Ca-P, rhenania phosphate-like product, single superphosphate-like product) from six recovery pathways. Using this case study, it demonstrates the application of the *end-user perspective* to develop a life cycle inventory and to understand the potential life cycle environmental impacts at the end user's product system.
The results show that the substitution reduces global warming, smog formation, acidification, eutrophication, and ecotoxicity potential of the assessed crop production system in most recovery pathways and scenarios. As more wastewater-derived products being available, the *end-user perspective* introduced can (i) complement with the *process perspective* and the *product perspective* to give a more holistic picture of environmental impacts along the "circular economy value chains" of wastewater-based resource recovery, (ii) enable systemwide environmental assessment of wide uptake of wastewater-derived products, and (iii) draw attention to understanding the long-term environmental impacts of using wastewater-derived products.

References

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The water-energy nexus in a drinking water supply system

Tuesday, 4th July - 12:14: Water 1 (short presentations) (C0.06 KOG)

Francesco Arfelli [1], ***Luca Ciacci*** [1], ***Fabrizio Passarini*** [1]
1. *University of Bologna*

The balance between water supply and demand is an essential issue, marked over time by political and environmental conflicts, as well as the impacts of natural disasters and the daily demand for several uses. The water issue is also mainstreamed by the United Nations that, in the “2030 Agenda for Sustainable Development”, included “Clean water and sanitation” between the 17 sustainable development goals. The balance between drinking water supply and demand implies the investment of resources aimed at optimizing resource management as well as proper understanding of the environmental consequences associated with techniques and operations implemented in a drinking water supply system (DWSS).
With this goal, this study applies life cycle assessment (LCA) to a DWSS located in the Romagna region in Italy, with the aim to analyze the system and to compare, from an environmental perspective, three water sources namely dam water (RD), surface water (SW), and groundwater (GW), and two water purification technologies (i.e., conventional treatment and ultrafiltration). Identification and quantification of the main water and energy flows was achieved by applying material flow analysis (MFA) techniques, providing a scientific basis for the analysis of interlinkages between the water and energy in the regional context. 1 m^3 of delivered drinking water was set as the functional unit, while system boundaries followed a cradle-to-gate approach. ReCiPe 2016 is applied as the impact assessment method.
The LCA results showed the best environmental performance for RD water treated with the conventional technology, although the impact of dam infrastructure is greater than that of alternatives. GW is purified in conventional plants, but the high electricity demand of the withdrawal process makes this process the most carbon intensive. SW, instead, is affected by a significant amount of electricity required to pump water through the membranes in the ultrafiltration stage. Electricity dominates the potential contribution to fossil resources scarcity (71.0%), global warming (62.7%) and particulate matter formation (41.2%). Infrastructure is the main contributor to human carcinogenic toxicity (34.2%), followed by aluminum sulphate, aluminum chloride and electricity. Charcoal prevails for land use (28.4%), followed by sodium hypochlorite, and aluminum sulphate/chloride. Because DWSS is highly energy demanding, sensitivity analysis clearly points out a significant decrease of environmental impacts if higher shares of renewable sources are utilized in the electricity grid mix, marking a clear way for de-carbonization of DWSS.
Water-energy interconnections provides more in-depth understanding of the water-for-energy and energy-for-water implications related to the provisioning of drinking water. Despite electricity consumption is a main contributing input to drinking water supply, the water sector is responsible for a limited portion of the regional electricity consumption (about 0.5% of the total generated). On the other hand, the volume of water involved in hydroelectric energy productions corresponds to the 83% of the system water inflow, disclosing an essential role water in the regional de-carbonization perspective.
LCA, MFA and the nexus analysis confirm to be fundamental frameworks for system-thinking approaches, which may ultimately support decision-makers and local communities to the planning of strategies for optimized and long-term reliable access to natural resources, which represents one of the most urgent challenges to face in the coming years.
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Ecological network analysis of the life cycle impacts of drinking water and wastewater in Ukraine

Tuesday, 4th July - 12:21: Water 1 (short presentations) (C0.06 KOG)

Oleksandr Galychyn [1], *Brian Fath* [2], *Nikita Strelkovskii* [3]

1. Finnish Environmental Institute (SYKE), 2. Towson University, 3. International Institute for Applied Systems Analysis

Water availability, a key sustainability issue at the city, regional, and national scales, depends on the supply and distribution of portable water as well as the sewage collection networks. This research focuses on Ukraine where, currently, regions in the east and south are supplied with 25.6% of the total water volume by redistribution from wastewater treatment networks, 70% of which are worn out. In addition, the longer residence time in the water distribution system leads to a decrease in water consumption. Ultimately, the rudimentary and over-reliant water distribution and wastewater treatment networks are unable to serve the population, resulting in sewage and water leaks that are harmful to human and ecosystem health alike. In this context, the incomplete understanding of services in monetary terms associated with Ukrainian economic sectors on public water supply may lead to an underestimation of water supply impacts and omission of their indirect portion from the analysis. Therefore, LCA studies should include the full economic contribution of the national economy and the rest of the world required to provide water supply to identify the contributing products and services to the environmental impacts of drinking water and wastewater and the stability of economic sectors (contribution of each sector to the other sectors) associated with these products, and services based on the ecological goal functions (maximize power, cycling, storage, and residence time). The goal functions help to connect the stability of sectors associated with products and services of the Ukrainian economy using their flow, storage, cycling, and residence time contributions to the other sectors and, ultimately, to the environmental impacts of water and wastewater.

In this paper, an integrated hybrid LCA method is presented, which includes the water supply and wastewater treatment process (process LCA) and the exchange of contributions (activities) by the water supply and water treatment sectors (information on products and services bought and sold by the water supply and water treatment processes) and by other sectors of the Ukrainian economy including information on products and services bought and sold by non-water industries. By expanding the upstream and downstream boundaries of the analysis, this approach not only provides a missing link between the indirect economic contributions to the environmental impacts associated with drinking water and wastewater, but also directs the development of the Ukrainian economy, water supply, and wastewater treatment networks toward improving the consumption rate of drinking water and reducing the impact of wastewater on air emissions (e.g., CO_2, N_2O, and NO_x) through the perspective of an ecological network. The results are expected to identify the sectors that require maximization of the associated goal functions to minimize their water and monetary contribution to the environmental impact of water and wastewater without jeopardizing their stability in terms of minimization of goal functions. This multi-method approach will help governments holistically manage the transition of their economies, water supply, and wastewater systems toward stability and sustainability by improving resource cycling, functional efficiency, and water security.

Carbon, water and economic benefits of infrastructure symbiosis between coal power and wastewater treatment

Tuesday, 4th July - 12:28: Water 1 (short presentations) (C0.06 KOG)

Yang Guo [1], ***Denise Mauzerall*** [1], ***Yizheng Lyu*** [2], ***Wanqiu Hu*** [3], ***Jinping Tian*** [2], ***Lyujun Chen*** [2]

1. *Princeton University,* ***2.*** *School of environment, Tsinghua University,* ***3.*** *Tsinghua University*

Symbiotic infrastructure systems facilitate deep decarbonization and efficient water use more than independent improvements in each type of infrastructure. Here we analyse strategies for bridging the coal power and wastewater treatment sectors in China by using sludge and reclaimed water from municipal wastewater treatment as alternative fuels and water sources for coal power generation. We develop a geodatabase covering ~2,400 coal-fired power plants and ~4,200 municipal wastewater treatment plants and conduct an integrated analysis using a customized optimization algorithm and life-cycle assessment. Such infrastructure symbiosis annually offers greenhouse gas (GHG) mitigation of 8.6 Mt CO2 equivalent, equal to 29% and 0.28% of GHG emissions from the wastewater treatment and coal power sectors, respectively. The symbiosis annually conserves 3.0 billion m3 of freshwater, equal to 62% of freshwater consumption by the coal power sector, and provides annual cost savings of 7.5 (3.4–12) billion CNY. Hebei, Shandong, Henan, Jiangsu, Zhejiang, Anhui and Guangdong contribute ~50% of GHG mitigation and ~60% of both freshwater conservation and cost savings due to the proximity of coal power and wastewater treatment plants. Approximately 80% of carbon, water and economic benefits can be achieved via 32% and 44% of all the plant-level linkages for sludge co-combustion and water reuse, respectively. Infrastructure symbiosis provides promising opportunities for both environmental and economic benefits. Policies to boost the establishment of energy–water infrastructure symbiosis would cost-effectively facilitate the achievement of China's climate and water targets.

Overconsumption of freshwater hidden in agricultural production and international trade

Tuesday, 4th July - 12:35: Water 1 (short presentations) (C0.06 KOG)

Nguyen Tien Hoang [1], ***Masaharu Motoshita*** [2], ***Keiichiro Kanemoto*** [3]

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Water is a finite resource, yet its value is infinite to human well-being and ecological sustainability. The United Nations World Water Development Report 2021 highlighted that freshwater is currently scarce, and becoming even scarcer. Despite efforts to promote sustainable agriculture, food and agricultural production remains the primary driver of freshwater scarcity and groundwater depletion around the world. However, it is still unclear where food production leads to overconsumption of freshwater, nor which products and countries are the most significant contributors. Here we quantify and map how production and consumption of 46 agricultural commodities driven by 197 countries deprive the essential freshwater requirement of ecosystems, at a pixel level. We find that overconsumption of freshwater varies greatly among agricultural commodities. Major cereals (wheat, rice, and maize), cattle, sugar cane, and cotton contribute significantly (65%) to the total overconsumed freshwater amount due to their large production volume. The same commodities can pose different overconsumed levels depending on their production area. India and China have the highest overconsumed freshwater amounts embedded in both agricultural production and consumption. Globally, while domestic demand is responsible for 91% of overconsumed freshwater, several developed countries, such as Japan, Germany, the UK, Korea, and Canada, have 95-100% of their overconsumed freshwater footprints in foreign countries. Our study provides a crucial scientific basis for managing freshwater usage efficiently through decisions concerning food consumption, production, and international trade. The ability to distinguish where commodities are produced in areas of overconsumed freshwater can help companies screen their supply chains to avoid such freshwater overconsumption hotspots.

Flows and emissions (short presentations)

Footprints of the wasteful dragon: Quantifying China's food loss and waste and embodied environmental impacts

Tuesday, 4th July - 12:00: Flows and emissions (short presentations) (B0.25 KOG)

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Food loss and waste (FLW) hampers global food security, human health and environmental sustainability. A good understanding of the availability and quality of global FLW data is a prerequisite for tracking progress on reduction targets, analyzing environmental impacts, and exploring mitigation strategies for FLW. By examining more than 300 publications which reported FLW data and quantified the environmental impacts of FLW generation and treatment, we found that significant challenges remain, such as data inconsistency and a narrow temporal, geographical (conducted for a few industrialized countries like the United Kingdom and the United States), and food supply chain coverage (mainly focused on the retailing and consumer levels). Consequently, monitoring and benchmarking FLW reduction is often constrained by lack of reliable and consistent FLW data, especially for emerging economies. Here based on six-year large-scale field surveys and literature data, we systematically quantify the FLW of major agrifood products along the entire food supply chain in China by using material flow analysis approach. We then calculated relevant resource and environmental footprints associated with the FLW from farm to fork. We show that 27% of food annually produced for human consumption in China is lost or wasted, with 45% occurring at postharvest handling and storage and 13% from out-of-home consumption activities. We also show that the total FLW resulted in large land, water, carbon, nitrogen, and phosphorus footprints, equal approximately to a medium-sized country (e.g., the United Kingdom's in the case of carbon footprint). These data provide a good basis to further discuss the role that reducing FLW can play in combating hunger, increasing resource efficiency and lowering environmental burdens. The system mapping framework we developed can also be adapted for applications in other emerging economies. The results highlight the importance and urgency for more consistent and reliable primary data to inform FLW reduction actions and ensure food security and sustainability.

Carbon Emissions from China's Plastic Production and Consumption

Tuesday, 4th July - 12:07: Flows and emissions (short presentations) (B0.25 KOG)

Yucheng Ren [1]***, Jian Jiang*** [1]***, Meng Jiang*** [2]***, Bing Zhu*** [1]

1. Tsinghua University, 2. Norwegian Univ. of Science and Technology

Plastics are widely utilized and play a crucial role in modern society, but they also pose certain environmental challenges. From a life cycle perspective, plastics are responsible for a large amount of fossil hydrocarbon consumption and greenhouse gas (GHG) emissions. By 2050, plastics are expected to account for 15% of the annual carbon budget. China is the world's largest plastics producer and consumer. Developing decarbonization strategies can be aided by a comprehensive study of China's life-cycle GHG emissions of plastics.

In recent years, some research has been conducted on plastics in China and the carbon emissions they produce, but our systematic understanding of material requirement, energy consumption and carbon emissions thoughtout plastic production processes remained unclear. The complexity of the chemical processes involved in plastic production, as well as the fact that there are multiple routes for these processes, presents one of the greatest obstacles in plastic production research. There are also significant differences in plastic production methods between China and other regions. To address these issues, it is necessary to develop a China-specific database covering the entire plastics life cycle, especially for plastic production. To analyze this complex system, however, combining material flow analysis and life cycle assessment presents a challenge.

Based on China's actual situation, we constructed a database of major plastics' (PE, PP, PVC, PS, ABS, and PET) life cycle carbon emissions. Specifically, we trace the carbon emissions throughout the plastics' industrial chain from the extraction of fossil resources to resin production in China. We incorporated 262 process units for the production, manufacture, trade, use, and disposal of plastics, covering 110 substances, including raw materials, products, energy, and emissions. We combined MFA and LCA to calculate the carbon emissions from the life cycle of six major plastics in China between 2015 and 2020. We demonstrated key plastic carbon emission sources in order to provide policy recommendations.

Results indicate that the intensity of carbon emissions from plastics in China is decreasing, while the total emissions are gradually increasing from 2015 (220 Mt) to 2020 (350 Mt). PVC, PP, and PE contribute to the highest life-cycle carbon emissions, reaching 121, 100 and 70 Mt in 2020, respectively. The production of chemicals accounts for nearly 80% of annual carbon emissions, in particular the calcium carbide process for PVC, coal for olefin, and naphtha cracking. Processes involving coal produce a greater proportion of emissions. At the end-of-life stage, landfill reduction and increased incineration increase carbon emissions slightly, while plastic recycling can significantly reduce carbon emissions.

Mitigation of carbon emissions shall focus on the phase of chemical products with the highest emission intensity. Our findings indicate the need for future technological advancements, such as breakthroughs in plastic production technology, the transition to a low-carbon energy source, enhancement of chemical and mechanical recycling, biomass plastic applications, and negative emission technologies. With scenario analysis tools, this work could provide a basis for a comprehensive assessment of China's future potential for the decarbonization of plastics.

Global flow of timber embodied in trade from income-based perspective

Tuesday, 4th July - 12:14: Flows and emissions (short presentations) (B0.25 KOG)

Chang Yu [1]

1. *Beijing Forestry University*

As the largest ecosystem on land, the forest plays a vital role in mitigating global warming and maintaining biodiversity. The 15th goal of the United Nations Sustainable Development Goals pointed out that deforestation and desertification caused by human activities and climate change pose a significant challenge to sustainable development and affect millions of people's livelihoods. Furthermore, the twenty-sixth session of the Conference of the Parties (COP26) to the United Nations Framework Convention on Climate Change (UNFCCC) held in Glasgow, UK, in 2021 announced "Glasgow Leaders' Declaration on Forests and Land Use," committing to halt and reverse deforestation and land degradation by 2030. However, the timber market demand in developed countries and emerging economies continue to expand, and timber trade activities have further deepened the deforestation of forest resources. The division system of the global value chain has separated the primary factor inputs, timber production, and consumption in the different countries. Scholars have analyzed the cross-regional flow of timber resources from production-based and consumption-based perspectives. However, existing research has not adequately analyzed key countries and sectors from the perspective of primary inputs. Ignoring the role of primary inputs on the timber production chain would underestimate the impact of certain countries or sectors on global timber harvests.

This study aims to identify the crucial primary suppliers that drive the flow of timber embodied in trade with the Ghosh-MRIO model. Meanwhile, we apply structural decomposition analysis (SDA) to reveal the influencing factors of the change of embodied timber in trade. Structural path analysis (SPA) is used to identify the key sectors driving the embodied timber flow. Moreover, combined with the Leontief-MRIO model, a comparative analysis is carried out to analyze the different results of the income-based, production-based, and consumption-based methods. It shows the significant role of primary input countries in the timber supply chain. The research results can help clarify the flow of forest resources embedded in global trade activities. Furthermore, it also provides a scientific basis to achieve better the forest resource protection goal agreed upon in COP26.

Factors driving China's carbon emissions after the COVID-19 outbreak

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:21: Flows and emissions (short presentations) (B0.25 KOG)

xinlu sun [1], ***Zhifu Mi*** [1]

1. University College London

The COVID-19 pandemic has swept across the world and exerted a profound impact on China's economic development and carbon emissions by halting economic activities as well as structural changes. Previous studies have a lack of data and therefore focused on quantifying the changes in carbon emissions rather than identifying structural changes in the driving factors of carbon emissions.

The authors of this study use the latest China input-output table and apply structural decomposition analysis to investigate the pattern changes in the driving factors of carbon emissions in China from 2002 to 2020, especially the structural changes in 2020. Carbon emissions are decomposed into five determinants (per capita consumption, population, production structure, consumption patterns, and energy efficiency) and the potential structural changes caused happened after COVID-19 are analyzed.

In the study, the authors show that the most significant change in the driving factors of carbon emission growth in 2020 is production structure, the contribution of which had declined since 2007 but rebounded in 2020. The changes in production structure were because of lower production efficiency and reliance on carbon-intensive inputs. Lower production efficiency indicates that the intermediate input intensity became higher in 2020, meaning that more intermediate input was required to produce the same amount of output. This usually represents less value-added created and lower productivity. The reliance on carbon-intensive inputs was shown by the increased proportion of carbon-intensive inputs in total inputs increased in 2020, for example, the preference for fossil fuels in the transport sector. Due to the halted economic activities in the first half of 2020, the contribution of per capita consumption to emission growth declined.

Therefore, the authors suggest increasing investment in low-carbon industries to avoid future carbon emission trajectories locked in the high-carbon industries and increasing the proportion of consumption in GDP to decrease the carbon intensity of final demand and to achieve a green and robust economic recovery from the pandemic.

Socioeconomic drivers of India's rising atmospheric mercury emissions

Tuesday, 4th July - 12:28: Flows and emissions (short presentations) (B0.25 KOG)

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Relevance: India is a top anthropogenic emitter of atmospheric mercury (Hg) whose emissions have been projected to continue rising in the future. Key factors driving these emissions are India's growing economy, its position in international trade, industry transition, increasing population and associated growth in consumer demand. An analysis of the influence of global (i.e., domestic and international) socioeconomic developments on India's Hg emissions is critical to better manage its Hg emissions problem. The implications of this study can play an important role in guiding national Hg emissions control policies and multilateral efforts to realise the objectives of the Minamata Convention on Mercury.

Approach: Our study is based on environmentally extended multi-regional input-output (EE-MRIO) analysis and includes three steps. First, using the Leontief model we study the trade-related drivers (in terms of final demands of nations and their sectors) of India's Hg emissions. Second, we conduct a structural path analysis (SPA) to identify the most relevant global supply chains driving Hg emissions in India. Third, we conduct a structural decomposition analysis (SDA) to identify the global socioeconomic determinants (emissions intensity, economic structures, populations, and consumption patterns) whose changes were responsible for India's Hg emissions increase over time.

The analysis is based on our previous work on India's Hg emissions inventory and drivers for 2004-2014[1], which is updated in this work and extended up to 2017. In addition to the inventory update, the novelty of this work lies in the SDA conducted from the demand perspective for four intervals: 2004-2007, 2007-2011, 2011-2014, and 2014-2017.

Key results: India's Hg emissions increased to 211 tonnes (t) per year in 2017 (12% higher than in 2014). 86% of the emissions are due to the domestic demand mainly from sectors related to construction, use of dental amalgam, waste disposal, electricity, transport, and manufacturing. 14% is due to foreign demand associated mainly with construction and manufacturing sectors. The top nations driving these emissions were the USA, UAE and China.

While examining the roles of different socioeconomic factors, we find that the domestic per capita final demand level change was the largest cumulative driver and led to an 87% increase in emissions between 2004-2017. This was followed by the rise in domestic population (17% increase), change in per capita final demand level (6% increase), change in economic structure of foreign nations (4% increase), and population of foreign nations (3% increase). Hg emissions decreased due to a change in domestic emission intensity (13% decrease) and a change in the domestic economic structure (4% decrease).

The assessment of different time intervals shows that the roles of these factors can be vastly different from the cumulative effect. For instance, India's Hg emission intensity change led to 32 t of decrease in emissions during 2004-2007, whereas it led to a 30 t increase during 2007-2011. It led to 3 t and 12 t of decreases during the next two periods. Discerning these trends can provide insights into the role of global socioeconomic development in India's increasing Hg emissions and guide sector-specific policy intervention and the optimisation of emission intensities, consumption patterns and economic structures to achieve low Hg emissions trajectories in India.

References:

(1) Jetashree; Zhong, Q.; Zhou, H.; Li, Y.; Liu,Y.; Li, J.; Liang, S. Role of Trade in India's Rising Atmospheric Mercury Emissions. Environ. Sci. Technol. 2022, 56 (2), 790-803.

On the way to food self-sufficiency in 2030: The case of Singapore's food stock flow

Tuesday, 4th July - 12:35: Flows and emissions (short presentations) (B0.25 KOG)

Ludwig Paul Cabling [1], *Lynette Cheah* [2]

1. University of Victoria, 2. Singapore University of Technology and Design

The island-state of Singapore currently imports more than 90% of its food from over 170 countries and regions. To reach Singapore's '30-by-30' target of meeting 30% of its nutritional requirements domestically by year 2030, thereby achieving greater levels of food security, further action needs to be done to address the nation's food loss and waste. This study presents historical food stock and flows of Singapore in the past decade, identifying trends in food demands primarily satisfied by imports. Increasing local food production in Singapore is one of the key goals to achieve greater self-sufficiency for the country, and assessing the nation's food system may reveal the extent of circularity achievable in the next decade. This study uses publicly available data from the Singapore Department of Statistics and National Environment Agency to present optimistic and pessimistic pathways to a self-sufficiency ratio (SSR) of 30%. Presently, Singapore will need to produce over 250,000 tonnes more food locally to achieve the 2030 goal. In previous years, resource- and land-intensive livestock-based products (beef, pork, and mutton) make up a lower fraction of the food demands of Singapore and may be a secondary focus for local food production, whereas over 60% of food consumed are fruits and vegetables. Beyond identifying opportunities for local fruit and vegetable production, seafood production can be targeted to either increase coastal/land-based farming or local landings. Visualizing Singapore's food stock-flow may enable policy makers to consider circularity, for instance, targeting specific waste streams for composting to support local food production. We find underexplored potential, particularly relating to recovering food waste streams for other purposes. As food consumption increases alongside steady population growth in the coming years, strategies such as composting and food waste recycling can target hotspot areas of food waste loss throughout the food system, such as from packaging and distribution losses. Other components of key importance identified in the presented food stock-flow were distinguishing food consumption either from households or from food establishments as different solutions exist to address food loss and recycling. Identifying the historical trends on production and post-harvesting & storage losses in the stock-flow diagram can inform priorities to tackle increased levels of food waste loss as Singapore continues to increase local food production, particularly for fruits and vegetables. Further, Sankey diagrams of the food category distributions of Singapore's food consumption can inform which food categories to prioritize depending on where products are imported from. Such work is needed to advance knowledge of city-scale food-waste linkages and stimulate policy efforts to meet sustainable development goals.

Scenarios (short presentations)

Methodological framework for scenario analysis of national consumption-based greenhouse gas emissions

Tuesday, 4th July - 12:00: Scenarios (short presentations) (B0.31 KOG)

Johannes Morfeldt [1]***, Jörgen Larsson*** [1]***, Daniel Johansson*** [1]
1. *Chalmers University of Technology*

A Swedish political process has proposed long-term emission reduction targets for Swedish consumption-based greenhouse gas emissions to be adopted in parallel with Sweden's territorial commitment – net-zero by 2045 – under the United Nations Framework Convention on Climate Change. The proposal includes a net-zero target by 2045 for consumption-based emissions with two alternative emission reduction targets for the Swedish parliament to consider and the remaining emissions being offset by other measures. The main target proposed is a 66% reduction of consumption-based emissions and the alternative and more ambitious target is a 77% reduction, both to be achieved by 2045 compared to 2010. Scenario analyses are needed to assess the proposed targets' ambition level and understand the policy implications of adopting these targets.

This study develops a hybrid framework for scenario analysis using a prospective lifecycle assessment. The framework considers how emissions will change over time in response to climate policy, technology development, and changes in consumption patterns. Prospective lifecycle assessment considers foreground systems (e.g., shifts in travel mode choices or adoption of new technology) in parallel with background systems (e.g., manufacturing processes). Domestic scenarios are designed to capture the impacts of territorial climate targets, changes in consumption patterns, and technology adoption. The domestic scenarios are combined with global decarbonization pathways (based on results from integrated assessment modeling) to understand the impact on emissions occurring abroad. The two global decarbonization pathways are (i) current trends and policies and (ii) a global climate transition in line with the Paris Agreement's goals.

The hybrid aspect of the framework denotes the combination of bottom-up simulation models for key consumption categories – air travel, passenger car travel, public transport, construction, space heating and household electricity, and food consumption – and a top-down approach for remaining consumption categories. The bottom-up simulation models are based on systems dynamics methods, such as stock-flow modeling and material-flow analysis. The top-down approach is based on data from the multi-regional input-output model Exiobase and uses an extended Kaya identity combined with results from integrated assessment models to estimate future emissions for these consumption categories. The hybrid framework enables detailed analyses of changes in consumption patterns and technology adoption for the bottom-up simulated categories. Meanwhile, the top-down approach allows us to estimate the impact on total consumption-based emissions and identify areas for further analysis.

Preliminary results show that the proposed main target would not be achieved by implementing measures in response to the currently adopted territorial net-zero target for 2045. Our results show that achieving the territorial target reduces consumption-based emissions by 35-62% in 2045 compared to 2010, depending on the global decarbonization pathway. Implementing policies and measures in addition to the territorial target that affects consumption patterns and technology adoption could further decrease emissions to a level of 49-71% in 2045 compared to 2010, depending on the global decarbonization pathway. Hence, such policies and measures put the proposed target within reach, if global decarbonization follows a pathway in line with the Paris Agreement's goals. However, neither of the analyzed scenarios achieves the proposed alternative trajectory. Moreover, future consumption-based emissions are strongly dependent on the global decarbonization pathway in all scenarios.

Dish-specific trade-off and scenario analysis can inform sustainable diet selection in Japan

Tuesday, 4th July - 12:07: Scenarios (short presentations) (B0.31 KOG)

Yin Long [1], ***Liqiao Huang*** [1], ***Lie Sun*** [1]

1. *The University of Tokyo*

Achieving sustainable dietary change is essential for safeguarding human and environmental health. Studies have proposed the characteristics of such sustainable diets and explored scenarios of their possible impacts using broad food groups (e.g. vegetarian diets). Although such broad-based approaches can provide a direction of how sustainable diets might look like and how to achieve them, in reality, individuals select and consume dishes that combine multiple food items. More importantly, these choices are informed by diverse context-specific factors including the local availability of food items and cultural sensibilities. Here we develop a novel approach to explore key sustainability trade-offs of dietary choices at the dish-level, and identify sustainable dietary options. We apply this approach to Japan, a national context with very unique culinary traditions, using 45 popular dishes that cover all major broad-based dietary categories (e.g. vegetarian, pescatarian). For each dish we estimate the nutritional quality, price and carbon footprint, considering all major and minor ingredients and the cooking method. Subsequently, we explore whether and how 16 sample dietary scenarios combining these dishes can meet nutrition requirements while minimizing carbon footprint. Overall, compared to more restrictive diet scenarios, mixed diets contain a higher combination of dishes that meet nutritional requirements at comparatively low carbon footprints. We argue that our approach complements well-existing approaches to understanding the trade-offs of diets and identifying sustainable diets by offering nuanced information at national and sub-national levels.

Meaning before measure: A review and critique of reported methods to quantify SDG interlinkages

Tuesday, 4th July - 12:14: Scenarios (short presentations) (B0.31 KOG)

Rega Sota [1], ***Sandra Venghaus*** [1]

1. *School of Business and Economics, RWTH Aachen*

Over the past decades, the concept of ‚sustainability' has evolved into a comprehensive leitmotif guiding essentially all aspects of humanity including our understanding of social and economic life, and our relationship with natural resources and the environment. While the concept was long criticized for its insufficient operationalization, the UN 2030 Agenda for Sustainable Development adopted by all UN member states in 2015 provides a sound political target framework. Its backbone are the 17 Sustainable Development Goals (SDGs) further refined into 169 targets measured by 231 indicators. Since then significant research has addressed both the current state of progress towards goal achievement as well as the interlinkages among individual goals and targets on various scales. Whereas significant progress has been made on quantifying certain SDG indicators or selected SDG interlinkages mostly on a regional scale, a substantial research gap yet remains especially with respect to a mutual understanding and definition of interlinkages as well as adequate methods to quantify them. Such lack of a shared methodology to refer quantitatively to SDG interactions was responsible for why the SDG interactions were initially studied through a qualitative lens or only through restricted nexus approaches. Following the qualitative attempt of Nilsson et al. (2016) to introduce numerical nuance in the classification of SDG interlinkages through a spectrum ranging from supporting to hindering interactions, interlinkage analysis has spanned into the quantitative realm. Numerous quantitative methods are reported in the literature for analyzing SDG interlinkages. While Nilsson et al.'s contribution claims to move away from the synergy/trade-off dichotomy that has long dominated interlinkage analysis, their suggestion has only strengthened this duality by providing unquantifiable nuances between the poles. Two main trends have been observed in the development of quantitative analyses for SDG interlinkages. In the first, correlation analysis, a pioneering framework in analyzing the interactions between indicator time series, has been continuously adopted, but each time with incremental or problematic improvements and with acknowledgments of newly identified shortfalls. In the second trend, the preferences lie either in more established econometric methods, such as goodness-of-fit from linear regression methods, attempts to quantify different SDG achievements through the units of a specific one (e.g., through SDG 7), or, alternatively, the reliance on mixed methods, which combine expert judgement, qualitative scoring and network analysis. The analysis of SDG interactions has moved away from correlation as the go-to method, yet instead of a unification, the field has grown more fragmented.

Based on the results of our systematic review of over 90 research articles, we argue that the reported quantitative methods applied to the study of SDG interlinkages so far do not rely on a consistent vocabulary, present methodological incongruences and involve errors. The deficiencies are grave enough to impede comparability of results between methods and to allow the publication of lacking papers. Given this lack of consistent definitions of interlinkages, there can be no robust identification of interlinkages, observations about their directionality or causality, application of data imputation or compression methods, classification of them into categories and neither can interlinkages lend any support to efficient policy making if the research community does not first define the meaning of SDG interlinkage and its finitely many types. Proceeding by any other course of action is akin to putting the cart before the horse.

Scotland’s Net Zero by 2045: Modeling metabolic potentials and scenarios toward emissions reductions.

Tuesday, 4th July - 12:21: Scenarios (short presentations) (B0.31 KOG)

Jean Boucher [1], ***Keith Matthews*** [1]

1. *The James Hutton Institute*

Societal metabolic analyses (SMA) offer a multi- and cross-scale method of understanding energetic and material flows at societal and other levels. SMA define and integrate views of: industrial sectors; workforce capacities; land use patterns; energy carriers and end uses; gross value added, and other primary material flows. Metabolic analyses can provide useful insights into options for social, economic, and energy policy instruments and to test their coherence as plans to move toward the ‘greening’ of economies, ‘green recoveries’, net zero, and a more ecologically just world. With the case of Scotland’s ‘net zero by 2045’, we use metabolic analyses to assess the challenges and tradeoffs in trying to maintain stable household and paid-work sectors while transitioning to electricity, other low carbon energy carriers and end uses, and while activating greener activities in land use and other industrial sectors. Through a number of different scenarios, we find Scotland to be extremely challenged by social and economic tradeoffs in its quest toward net zero by 2045. Scenarios include: status quo, net zero, progress to net zero, and degrowth. Other societal metabolic constraints and tradeoffs are discussed.

Trade-offs between material efficiency and environmental performance for managing plastics packaging waste

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:28: Scenarios (short presentations) (B0.31 KOG)

John Laurence Esguerra [1], ***Annica Carlsson*** [1], ***Stefan Anderberg*** [1], ***Joakim Johansson*** [1]

1. *Linköping University*

The single-use function of plastic packaging generates a continuously increasing input to the waste management system leading to sustainability challenges. In response, several management strategies along the plastic value chain are proposed including improvements on product design, source-separation, mechanical and optical sorting, and further downstream material recycling. However, in some countries like Sweden, these strategies are often implemented in isolation without considering their combination effects on the performance of the entire plastic value chain. Moreover, the corresponding assessments of these strategies are often limited to material efficiency (i.e., recycling rate) thus overlooking the potential trade-offs with environmental performance. Hence, this study aims to assess the combination effects of different management strategies for plastic packaging in Sweden in terms of both material and environmental dimensions. Over 700 scenarios involving different combinations of management strategies were modeled and assessed through life cycle assessment. The results show that upstream strategies such us polymer restriction especially for food packaging (i.e., limiting to polyethylene terephthalate and polypropylene) lead to higher recycling rates and better environmental performance. In contrast, further downstream material recycling strategies show more apparent trade-offs, especially between recycling rates and environmental impacts related to toxicity. Recommendations for the combinations of management strategies for plastic packaging, which can increase recycling rates and reduce environmental impacts, are presented and discussed.

Enabling Shifts Towards Sustainable Circulation of Materials in Transportation Infrastructure: Development and Testing of an Approach Using Systems Thinking

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Scenarios (short presentations) (B0.31 KOG)

Sara Malmgren [1], ***Kristina Lundberg*** [2], ***Rajib Sinha*** [1]

1. KTH Royal Institute of Technology, 2. Ecoloop AB

How could enabling conditions for shifts from linear material flows towards sustainable circulation of materials in Swedish state transportation infrastructure be achieved? And more generally, how could possible paths towards enabling transitions and other shifts be identified, utilizing systems thinking to handle complexity associated with these, building on transition theory and knowledge of actors in the value chain? In a manner adapted to support policy development processes, focussing on identifying priority areas for interventions as well as development of chains of reasoning (as a basis for development of, e.g., impact logics)? This has been explored in this project, designed as a pilot project developing and testing an approach adapted for the purpose. Five semi-structured interviews were performed to collect data on major drivers for increased circulation of materials, system failures (Weber and Rohracher, 2012) impeding realization of sustainable circulation, as well as how system failures could be resolved. Sustainable circulation of materials here refers to circulation i) meeting quality requirements of the technical installation and with respect to its local environment as well as ii) realizing national economically cost effective measures for decreased impacts on climate change. A causal loop diagram describing how shifts towards sustainable circulation could be enabled was assembled building on the idea of Smith et al. (2005) of transition as a result of selection pressures and resources from within and outside of the regime mobilized to meet these. The model was also reformatted to a "transition logics" designed to support dialogue, and the possibility to develop a chain of reasoning based on the results was also demonstrated. Seven interacting main paths towards enabling shifts towards sustainable circulation were identified, including the following suggested priority areas for interventions: 1) digital systems for keeping track of materials including declaration of these as well as supply within a reasonable distance, 2) business models and complementary measures for co-ordination between flows, 3) development of conditions for using material with the right quality given its application, including standards, testing methods and prerequisites for taking decisions based on these, 4) investigating possibilities for development of regulations for decreased administration and equal demands on circulated and primary materials, 5) improved conditions for interpreting regulations, 6) learning related to use of circulated materials and 7) further development of a goals for sustainable circulation of materials in state transport infrastructure, including a description of market failures which need to be targeted. Possible next steps within priority areas for interventions were discussed, as were possible priorities in the near future building on, e.g., the framework for sustainable market transformation previously developed by Nijhof et al. (2022). Also limitations of the approach used in the project were discussed, and possibilities for further development of the approach to provide an improved knowledge basis for policy development striving to enable transitions and other shifts were explored.

Nijhof, A., Wins, A., Argyrou, A. och Chevrollier, N. 2022. Sustainable market transformation: A refined framework for analyzing causal loops in transitions to sustainability. *Environmental Innovation and Societal Transitions* 42(2022): 352–361.

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Mobility (short presentations)

How do active travel modes enhance transportation equity and why people don't use them?

Tuesday, 4th July - 12:00: Mobility (short presentations) (B0.13 KOG)

Utkuhan Genc [1]***, Hao Luo*** [1]***, Hua Cai*** [1]

1. *Purdue University*

Accessibility to alternative mobility options (besides car) is a key indicator of the quality of life in terms of physical, mental, and economic well-being. The car-dominant transportation system in the U.S. and the environmental justice issues regarding the transportation system (i.e. unequal impact of pollutants) is highlighting the importance of alternative travel modes and their roles in achieving healthy and sustainable communities. Until recently, transportation equity was only concerned with driver-related aspects such as fairness of transportation funding, while the impacts on other modes and their distribution were considered with little concern. It is important to provide communities with alternative travel modes because active travel modes such as walking and biking promote lower rates of smoking and lower BMI, lower the risk of cardiovascular disease, and have a positive association with the quality of life for the elder population. Aside from the direct health benefits, by lowering the exposure to contaminants the newer and cleaner travel modes can help us reverse the unjust burden of air pollution experienced by people of color. If the spatial and sociodemographic distribution of these transportation alternatives are not equitable, the physical, mental, and economic well-being of under-resourced groups is likely to decline. Evaluating the equity of active travel modes is vital to reduce these negative distributional impacts and inform better infrastructure development.

In general, analyzing travel time to alternative modes such as bus stops has been used to define transportation access. However, having access to certain trip modes based on proximity does not necessarily add to transportation equity. For example, if someone lives close to a bus station but the bus route that can be accessed does not align with this person's trip destination, they will not be able to use the bus as a feasible mode for this trip. In addition, biking and walking trips can be unsafe and inconvenient if there is no proper safe infrastructure along the origin–destination route which makes these options infeasible in car-centric areas.

This research focuses on assessing which transportation modes are feasible alternatives to serve a trip to understand if individuals have a choice for using healthier and greener alternatives. Additionally, if they do have a choice what are the key barriers to not using these alternatives? The recent development of information and communication technologies and open data efforts provide unprecedented opportunities for origin-destination-based analysis with respect to infrastructure availability. With these developments, it is now possible to evaluate if a travel mode is a feasible option with both cost- and quality-based measures. The cost-based method estimates the monetary and time cost of using each mobility option and compares it with prominent trip mode (car) to examine "forced car use" concerning travel demand. We checked how comfortable and safe a trip with a certain alternative would be using quality-based methods to understand key barriers of using these alternatives. We call the combination of quality and cost-based measures travel-demand-relevant access.

Preliminary key insights can be listed as (1) it is important to consider travel-demand-relevant access to evaluate transportation equity because we found that 40% of the trips that were identified as accessible by public transit are not feasible when travel-demand-relevant access is considered; (2) people with non-college educational attainment, households with more crowded rooms, and larger families are the negatively impacted groups from lack of transportation alternatives.

Assessment of Environmental Impacts for Autonomous Vehicle Data Management

Tuesday, 4th July - 12:07: Mobility (short presentations) (B0.13 KOG)

Kendrick Hardaway [1]***, Oscar Teran*** [1]***, Hua Cai*** [1]
1. *Purdue University*

Motivation

Autonomous vehicles (AV) pose an opportunity to reduce greenhouse gas (GHG) emissions through efficiency gains and by encouraging car-sharing and ride-pooling. However, there is at least one area in which they will require more energy and generate more emissions than conventional vehicles: the data management necessary for their operation. While several environmental assessments have included the energy required by the on-board computer and sensors, the supporting cyber-infrastructure's energy use and emissions have been completely neglected. By ignoring the transfer, storage, and cybersecurity necessary for AV data, we may be substantially overestimating the environmental benefits of this emerging technology. Therefore, in this study, we provide an initial analysis of the energy requirements and emission generation of the supporting cyber-infrastructure for an AV fleet in the United States.

Methods

We built a model that ties together research literature values from across the transportation, automation, and data management fields. In the *Data* subsection of the model, we estimate the total data generated in a year by a fleet of AVs. It accounts for the number of vehicles, the amount of use, and the sensors collecting data for the vehicle. In the *Energy* subsection of the model, we estimate the energy requirements for the computation, sensing, transferring, storing, and securing of the data. In the *Emissions* subsection, we estimate the GHG emissions of the energy demands calculated in the *Energy* subsection. We consider various market penetration rates, electrical power grid mixes, and efficiency improvements in the technology. For each value in the calculator, we performed sensitivity analyses. This is the first study to provide a quantification of the cyber-infrastructure needed for AV operation.

Results

We find that the supporting cyber-infrastructure system makes up 5-10% of all the energy requirements for AV data management. For having been ignored in previous studies, this is a substantial amount. Furthermore, we find that even if we manage a best-case renewable energy transition, a 40% penetration rate of AVs has a 1000% increase in GHG emissions from the base scenario. Though, as AV penetration rate increases, there is an inverse scaling impact for the storing of data. We find that the Waymo sensor composition produces the least GHG emissions of the company models tested. The connectivity of vehicle-to-vehicle, vehicle-to-user, and vehicle-to-infrastructure may offer the best tradeoff since it does not require as much energy and could improve fuel economy. Nonetheless, our results indicate that AVs data management has salient environmental impacts even with significant efficiency improvements to computation and data management.

Vehicle electrification & fuel electrification: Two complementary paths to decarbonize China's passenger road fleet

Tuesday, 4th July - 12:14: Mobility (short presentations) (B0.13 KOG)

Jianxin Li [1], Xin Sun [1], Jon McKechnie [2], Amir F.N. Abdul-Manan [3], Li Fu [1], Xianhui Jiao [1], Jinlong Wu [1]

1. AUTOMOTIVE DATA OF CHINA CO., LTD, 2. Sustainable Process Technologies, Faculty of Engineering, University of Nottingham, Nottingham NG7 2RD, 3. Strategic Transport Analysis Team, Fuel Technology R&D, Research & Development Center, Saudi Aramco, Dhahran, 31311

China has pledged to peak GHG emissions by 2030 and achieve carbon neutrality by 2060. Addressing the emissions from transport will be key to achieving these ambitions. Electrification of passenger vehicles is considered a promising option, however, its GHG mitigation potential relies heavily on the accessibility to cleaner power sources. Furthermore, the speed of fleet decarbonization will be critically dependent on the adoption rate of electric vehicles (EV) and the vehicle turnover rate within the fleet. An emerging decarbonization option for the transport sector is low-carbon synthetic fuel, or also known as electro-fuel (e-fuel), which is produced from captured CO2 and clean hydrogen manufactured via electrolysis using renewable electricity. E-fuel is a low-carbon alternative to conventional fuels that can be used in existing vehicles in the fleet, thus it offers a promising option to accelerate the decarbonization of passenger road transport in China. However, the potential for e-fuel to decarbonize China's passenger vehicle fleet has not been properly quantified. Here, we develop a dynamic, fleet-based, life cycle assessment model using a bottom-up approach for China's passenger vehicle fleet. The study assesses and compares the decarbonization potential of EVs and e-fuel adoption from a life cycle perspective through a set of scenarios. We conducted sensitivity analyses on key parameters including the evolution of power grid mix, e-fuel production pathways, and battery GHG emission factor. Our analyses demonstrated that e-fuel can reduce total peak emissions and enable a faster GHG reduction progress, meanwhile EVs can offer significant mitigation potentials with a deeply decarbonized power grid. We find that EVs and e-fuels are complementary solutions that can facilitate an accelerated decarbonization for the passenger road sector, resulting in a lower cumulative GHG emissions between 2020 and 2060. This study provides valuable insights that can inform policy discussions in China, which, qualitatively, are also relevant to many other jurisdictions that aim to decarbonize their passenger road fleet.

Undoing the lock-in of urban sprawl: integrated modelling of materials and GHG emissions of urban transformation for decreasing car dependency

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:21: Mobility (short presentations) (B0.13 KOG)

Laura À. Pérez-Sánchez [1]***, Tomer Fishman*** [2]***, Paul Behrens*** [3]

1. Universitat Autònoma de Barcelona, 2. CML Leiden, 3. Leiden University, CML

The extensive penetration of cars has facilitated suburban sprawl, reinforcing further car dependency through the 20th century. The long lifetimes of suburban infrastructure present barriers to sustainable mobility, which would require a profound transformation in the densification of urban forms to enable the location of residents closer to services and work. Here we analyse the dilemma of prematurely demolishing single-family houses to densify urban forms by assessing the effects on land use, material demand and stocks and GHG emissions. We build an integrated Product Flow Analysis of dwellings and car ownership & use in Sweden by municipality type (2020-2100). The up-front carbon emissions in new construction for densification are only paid off in the long-term by the savings on mobility. These emissions savings are minor in the context of urgent, short-term decarbonisation and vary more with the level of electrification of transport. The denser final built environments may have further social benefits and free half the current residential land use.

Siting Solar Charging Stations for Shared Electric Bikes

Tuesday, 4th July - 12:28: Mobility (short presentations) (B0.13 KOG)

Yue Li [1], ***Hua Cai*** [1]

1. *Purdue University*

This study aims to address the challenges faced by the bike share systems that are incorporating electric bikes (e-bikes) into their fleets. Compared with traditional shared bikes, e-bikes offer improved performance, range, and speed, making cycling more attractive. By enabling longer trips, they also have the potential to reduce greenhouse gas emissions by replacing cars. However, the manpower required to replace and charge batteries increases the financial and operational costs of the system. To address this, researchers have proposed incorporating photovoltaic (PV) panels at bike share stations to charge e-bikes. However, previous studies have not taken into account the geographical and temporal variability of solar accessibility in urban areas. Additionally, adding large PV panels and batteries to all bike sharing stations would be costly and environmentally impactful. Optimizing charging capacities in different stations and leveraging existing bike share stations equipped with small PV panels can be a more cost-effective approach.

This study develops a solar charging solution for shared e-bikes that considers the spatiotemporal variability of solar PV potential in urban areas and optimizes the installation of PV panels at existing bike share stations. The study will estimate solar PV potential and energy consumption using real-world data and incorporate these into a location-allocation model to maximize coverage of the system's energy needs and minimize travel distance to charging stations. The study provides a modeling and optimization framework for implementing solar-charging stations for e-bike share systems and demonstrates the potential for using solar energy to improve the sustainability of shared transportation systems.

Low Carbon Development Strategies and Transformation Pathways of Automotive Industry

Tuesday, 4th July - 12:35: Mobility (short presentations) (B0.13 KOG)

Xin Sun [1], ***Jianxin Li*** [1]

1. *AUTOMOTIVE DATA OF CHINA CO., LTD*

The automotive industry, as the pillar industry of China's national economy, shows important carbon emission characteristics such as rapid growth of total carbon emissions and strong driving force to the whole industry chain. This study first, based on the China Automotive Life Cycle Assessment Model (CALCM), accounts for the life cycle carbon emission of single vehicle, enterprise and fleet of passenger vehicles and commercial vehicles sold in China in 2021, and analyzes and publicizes the current life cycle carbon emission of China's automobile enterprises and products; secondly, with carbon neutrality of the automotive industry as focus, puts forward from different perspectives ten transition paths, including clean electricity; vehicle electrification; fuel decarbonization; low-carbon material; production digitalization; transportation intelligence; shared mobility; resource recycling; carbon capture, utilization and storage; and product ecologicalization, sets up three scenarios namely reference scenario, low-carbon scenario and enhanced low-carbon scenario, and then fully discusses the carbon emission reduction potential of different paths under these scenarios; finally, based on the research results and the challenges facing the automotive industry at home and abroad under the carbon peak and carbon neutrality goals, points out policy measures and strategic suggestions for the low-carbon development of China's automotive industry, with a view to supporting the formulation of national carbon emission policies, promoting the R&D and application of low-carbon technologies, leading the automotive industry to achieve the carbon neutrality goal, and promoting the higher quality, more efficient and more sustainable development of automotive industry.

Transitions (short presentations)

The impacts of beachcast harvest on the nitrogen flows on Gotland, Sweden.

Tuesday, 4th July - 12:00: Transitions (short presentations) (B0.41 KOG)

Vita Xu [1], ***Jiechen Wu*** [2], ***Daniel Franzen*** [2]

1. KTH, 2. KTH Royal Institute of Technology

Macroalgal mass blooms and excessive beach-cast accumulation caused by changes in marine nutrients are increasingly alarming issues for a coastal region like Gotland. To maintain the recreational value of the coastline and utilize potentially valuable marine bioresources, a beach cast harvest project under the Swedish national water quality program LOVA (Swedish: Lokala vattenvårdsprojekt) has been implemented since 2009 to maintain the coastal environment and mitigate the eutrophication issue of the Baltic Sea. The use of dried beach cast as biofertilizer on local farmland is one of the many ways to utilize the harvested beach cast. This thesis explores the potential of beach cast as a nitrogen fertilizer and its role in Gotland's agricultural nitrogen cycle. The goal of the study is to evaluate the potential of beach cast fertilizer when larger quantities of beach cast are harvested and utilized and how it can reduce reliance on chemical fertilizer. By examining different compositions of nitrogen input into farming land, the study tracks the trend of nitrogen loss to the atmosphere and to the Baltic Sea.

The study delivers its results by mapping the nitrogen cycle of Gotland's agricultural sector and comparing the impact of an increasing amount of beach cast fertilizers on different nitrogen flows through seven beach cast utilization scenarios. The study reveals that nitrogen flows associated with livestock farming and chemical fertilizer have the largest quantity of nitrogen passages in the nitrogen cycle. The findings also indicate a positive impact of beach cast fertilizer on increasing the share of biofertilizers and reducing the use of chemical fertilizers in Gotland's agricultural sector. The nitrogen leaching to the Baltic Sea can potentially be reduced by up to 12.6% in the utilization scenarios. However, a slight increase in atmospheric nitrogen emissions by 0.1% is also identified due to the increasing share of organic nitrogen in the soil.

Due to the overwhelming quantities of nitrogen resulting from livestock farming processes and chemical fertilizer usage, the study concludes that replacing chemical fertilizer with beach cast in the near future is inaccessible. Despite this, beach cast fertilizer remains a commendable green alternative to chemical fertilizers and represents a significant opportunity for Gotland's transition towards a sustainable agricultural system. Nonetheless, the harvest and utilization of beach cast face challenges from various aspects: technical and financial barriers need to be assessed to facilitate the expansion of harvest activities, as well as the potential impact of beach cast removal on coastal ecosystems. Furthermore, addressing the identified knowledge gap between local authorities and farmers necessitates enhanced community engagement.

All in all, the study contributes to understanding the potential of beach cast as a biofertilizer and its interactions with the regional agricultural nitrogen cycle. By tackling the recognized difficulties and capitalizing on the possibilities, the potential of beach cast fertilizer can be maximized as a multi-purpose strategy for Gotland's local nutrient management.

Using integrated MFA approaches to model industrial transformation: Case studies from the construction sector in Germany

Tuesday, 4th July - 12:07: Transitions (short presentations) (B0.41 KOG)

Ali Abdelshafy [1], *Grit Walther* [1]

1. Chair of Operations Management - RWTH Aachen University

Material flow analysis (MFA) has been an effective approach for industrial ecology. Due to the increasing number of research questions and fields of industrial transformation, more methodological integrations and extensions are still required. Herein, this study presents three integrated MFA models, which have been derived and applied on three case studies. First, an intersectoral MFA model is developed to investigate the impacts and interdependencies of the transition of the energy system and the implementation of a circular economy. For example, the shift towards green steel will have an impact on the availability of blast furnace slag, which is used to produce CEM II and III. Also, the coal phase-out act in Germany will affect the amounts of fly ash and FGD gypsum. Herein, the model's framework consists of three consecutive steps. First, the production processes are studied and the relevant inflows, outflows and stocks are determined. Second, the identified inflows and outflows are quantified. Finally, the alterations caused by the industrial transformation are analyzed. The presented model and analyses can help the policymakers and strategists to understand the intra- and intersectoral relations, impacts of relevant policies, and the associated changes in the material and emission flows.
As the location has a crucial impact on the construction activities and relevant transportation costs, integrating the spatial dimension can be essential for certain analyses. Hence, the second model (spatial MFA) has been developed to consider both the locations and quantities of the relevant materials. Herein, the presented case study investigates the potentials of coupling a carbon capture and utilization technology (i.e. carbonation) with the supply chain of construction sector. Similar to the first model, the framework is composed on three phases. First an MFA model of the regional construction sector has been used to identify and quantify the construction products suitable for carbonation. Thereafter, detailed atlases of the relevant construction products and waste streams have been derived to determine the locations and quantities of the relevant flows. Finally, location-allocation models have been developed to optimize the routes between the CO_2 sources and relevant flows. Therefore, besides the quantifying the CO_2 sequestration capacities, the analyses also quantify the impact of transportation on the prospective carbonation supply chains.
Besides location, the time dimension is essential for some material flows and supply chains. Linking recycling operations with construction activities is mandatory for promoting circular economy in the construction sector. Hence, similar to the preceding model, integrating the spatial aspect is important for minimizing the transportation costs. Additionally, the temporal dimension is also important due to the changes in the patterns of supply and demand over time. Herein, the dynamic-locational MFA model has been derived to integrate both dimensions into one framework. The first step in the framework is identifying the relevant parameters and collecting the databases in order to conduct the empirical analysis. The survival and construction functions are then derived to forecast the future demolition and construction activities. Finally, the associated material flows are estimated in each locational and temporal unit. Accordingly, the supply and demand of secondary resources can be matched and the relevant strategies can be developed.

Sustainable land transition through area neutrality in municipalities

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:14: Transitions (short presentations) (B0.41 KOG)

Natchiyar Balasubramanian [1], ***Aleksander Storebø Bachke*** [1], ***Emma Tagseth*** [1], ***Ottar Michelsen*** [1]

1. *Norwegian Univ. of Science and Technology*

Globally, urban areas and especially cities are expected to triple in size by 2030. Urbanization is a major contributor to global land conversion and contributes to the global challenge of competition for land. The increased population and need for space lead to expansion into surrounding natural and agricultural areas, often neglecting the impacts on land and ecological systems leading to a reduction in the delivery capacity of ecosystems.
Although urbanization causes habitat degradation, increases invasive species, and inhibits ecosystem functions, it can also positively contribute to biodiversity. Urban areas can serve as refugia for plants and animals as well as support the landscape structure through positive and efficient land management strategies. The trade-offs and success are usually dependent on the governing bodies, area developers, and city inhabitants. Governing bodies such as municipalities also play a crucial role in implementing and operationalizing national and international policies related to biodiversity due to their role in area planning. In Norway, municipalities can be capable of designing sustainable landscapes as the major land planning authority and recently several municipalities have pledged to become area neutral. The main purpose of this framework is for municipalities to reduce their negative impacts on nature and achieve zero net loss. Municipalities around are putting forth their land management plans to achieve these commitments.
The municipality of Trondheim is one of the municipalities in Norway to have pledged area neutrality. Trondheim is one of the cities with a growing population and is expected to grow by 28% by 2050 up to approximately 250 000 inhabitants. This makes it a relevant city for a case study as the results can be applied in other growing cities around the world. The municipality has announced an area plan that aims to aid in achieving area neutrality through effective nature management, land use planning, and sustainable urban development.
In our study, we focus on the main stakeholders affected by the area plan, the inhabitants of Trondheim, area planners in the municipality, and area developers. We evaluate the perception of the inhabitants on the new area plan and biodiversity loss. This plan is expected to add pressure on municipality and area planners to avoid negative impacts on natural landscapes from construction and expansion. We are conducting interviews with these stakeholders, i) To understand their perceptions of area neutrality and biodiversity loss, ii) To understand the level of contribution towards net zero action plans, and iii) To what degree the operationalization of the term 'area neutrality' is useful also for reducing the loss of biodiversity. Additionally, we explore the interdependencies of local businesses and municipality regulations to provide better measures and policy recommendations, e.g. to what degree the suggested measures and incentives are able to capture the impact on biodiversity on a scale smaller than overall area planning. Finally, this study provides a holistic evaluation of the existing area plan and will contribute towards expanding the policy to make this ambitious area neutrality target achievable.
Key words: Area neutrality, municipality, biodiversity, Trondheim, land-use

Carbon neutrality of China’s passenger car sector requires coordinated short-term behavioral changes and long-term technological solutions

Tuesday, 4th July - 12:21: Transitions (short presentations) (B0.41 KOG)

Wu Chen [1]***, Xin Sun*** [2]***, Xiaojie Liu*** [3]***, Quansheng Ge*** [3]***, Edgar Hertwich*** [4]***, Gang Liu*** [1]

1. *University of Southern Denmark,* ***2.*** *China Automotive Technology and Research Center,* ***3.*** *Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences,* ***4.*** *Norwegian Univ. of Science and Technology*

Transportation plays a vital role in everyday life and is key to sustainable development. Transportation, however, also generates substantial CO2 emissions and will account for 40% of global CO2 emissions by 2030. Passenger cars account for almost half of all transport-related CO2 emissions and are particularly problematic in China, the world’s top passenger car consumer. Rapid decarbonization is therefore important but challenging, in China, where, despite recent emission peak (by 2030) and carbon-neutrality (by 2060) pledges, car ownership and associated emissions are increasing. Successful emissions reduction will require a rapid transition of both technology (e.g., toward electrification) and demand (e.g., driving less). However, how to successfully deploy these twin strategies for optimal outcomes remains unclear. Here, we develop an integrated car fleet dynamics model that considers time-cohort-type dynamics (e.g., the changes of car ownership, car powertrain technology, and car segment over time) and material-energyemission nexus (e.g., material demand, energy consumption, and full life-cycle emissions) and integrates demand- and technology-oriented parameters. Our model builds on China-specific bottom-up data and reveals the material and emission implications of China’s future passenger car transition under various individual or combined technology- and demand-oriented transition scenarios. Our analyses reveal that optimal short-term results will be achieved through demand-oriented strategies, which can reduce emissions by 22% and achieve 2030 emissions peak targets. Technology-oriented strategies are more optimal when deployed in the longer term and can result in emission reductions of 91%. A successfully coordinated strategy could reduce China’s passenger cars CO2 emissions to 0.05 Gt by 2050.

Demand and deployment of hydrogen liquefaction plants in Europe

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:28: Transitions (short presentations) (B0.41 KOG)

Alicia Torres Gomez [1], ***Graham Pullan*** [1]

1. *University of Cambridge*

The global hydrogen demand is predicted to rise to 425-650MtH2/year by 2050, which is 6-9 times the current pure hydrogen demand [1]. In particular, the liquefied hydrogen (LH2) demand is projected to be of 42MtH2/year for aviation [2] and 2-9MtH2/year for marine applications by 2050 [3,4,5]. Hydrogen international trade, much of which is expected to be in liquefied form, is forecast to reach $100-300 billion by 2050 (1000 times increase) [6].

State-of-the-art hydrogen liquefaction plants are based on simple low-efficiency Claude cycles with Nitrogen pre-cooling (Specific Energy Consumption (SEC) of 10.8-12.7kWh/kgLH2) [7,8]. Current European hydrogen liquefaction capacity is less than 30 tonnes per day (tpd) in total over 4 sites (France: 1, Netherlands: 1, Germany: 2) [9,10].

This research first quantifies the European LH2 demand by 2050. Then, the scale and efficiency of future plants is investigated. Hence, the number of liquefaction plants required over 14 European countries is forecast. Finally, the renewables capacity required is compared to achievable limits.

The overall energy system of 14 European countries is analysed using the EnergyPLAN software [11] and data from the EU Heat Roadmap Europe (HRE) project [12,13]. This project has two scenarios, business-as-usual (BAU2050) and ambitious (HRE2050), for 14 countries which are representative of the EU (90% of the population [14]).

The total hydrogen demand for Europe is of 200TWh/yr in the BAU2050 scenario and 2,600TWh/yr in the HRE2050 scenario. The electrolyser capacities required are 44 TW and 630 TW respectively. The spread of hydrogen demand and electrolyser capacities across Europe is shown cartographically. If a 100 MW electrolyser capacity corresponds to 48tpd of hydrogen [15] and 10% of all hydrogen produced is liquefied [16], the European liquefaction capacity required is 2,000tpd and 30,000tpd in the two scenarios respectively (66-1000 times the current capacity).

Current state-of-the-art plants each have a capacity <35tpd (<10tpd in Europe). However, as the LH2 demand rises, newly built plants will need larger capacity. Future plants are expected to be >50tpd, with some over 200tpd. This increase in plant scale shifts the economics from minimising CAPEX to OPEX and allows the introduction of more efficient components and processes (e.g. mixed refrigerant pre-cooling, Helium-Neon Joule-Brayton cooling, use of turbo-compressors, etc.). Therefore, plant efficiencies are expected to double from about 25% (SEC=13 kWh/kgLH2) to 50% (SEC=6.5 kWh/kgLH2) [10,17].

Based on a future average plant capacity of 100tpd, a map of the number of liquefaction plants required by country for each scenario was created. In total, 20-25 plants will be required in the BAU2050 scenario and about 300 in the ambitious scenario. In the BAU2050 case, only 3 countries need more than one 100tpd plant. In the HRE2050 scenario, the countries with the largest plant deployment will be Spain (51), UK (49), France (46) and Germany (42).

Finally, the HRE2050 renewables deployment needed is 1,200TW of wind and 250TW of solar. Maps showing the predicted deployment versus the achievable wind and solar capacities [18] for the 14 countries show that the solar capacity is realistic for all but four countries, but the wind capacity is unrealistic in most countries.

In summary, 20-300 hydrogen liquefaction plants of large capacity (~100tpd) and high efficiency (~50%) will need to be deployed by 2050 to meet the fast-rising demand of LH2 in Europe. The renewables deployment needed for this decarbonised scenario may prove challenging.

Towards Water Resource Recovery Facilities: An Integrated System Assessment of Emerging Sewage Sludge Management Technologies in Sweden

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Transitions (short presentations) (B0.41 KOG)

Wednesday, 5th July - 11:45: Water 2 (B0.16 KOG)

Harry Tibbetts [1], ***Lara Carvalho*** [2], ***Jiechen Wu*** [1], ***Sebastian Schwede*** [2], ***Ali Ahmad Shahnawazi*** [2]

1. KTH Royal Institute of Technology, 2. Mälardalen University

Municipal sewage sludge (MSS) management varies widely between countries and legislative regimes. Within the European directive for sewage treatment France applies over half of MSS to arable land, while The Netherlands has banned the practice (Kelessidis et al, 2012). In Sweden, 34% of MSS is applied to agricultural lands; despite this, official government reports recommend banning the practice over pollution concerns, alongside the most common alternative of land reclamation (Ekane et al, 2020). This is the result of two decades of disagreement, complicated by dual perceptions of MSS as a valuable resource to be returned to the ecocycle vs an unsanitary waste product requiring careful disposal (Ekman Burgman, 2022).
Previous studies have analyzed novel treatment technologies including multiple forms of phosphorus and nitrogen extraction from various stages of MSS treatment, but holistic system analyses are scarce (Bagheri et al 2023). Based on literature review and emerging technologies in Sweden, hydrothermal carbonisation (HTC) is identified as a keystone technology, and can be supported by secondary treatment via nitrogen stripping and phosphorus extraction from liquid and ash waste streams respectively. HTC is an anaerobic thermal treatment of wet organic waste resulting in solid hydrochar and liquid process water products. To address the lack of holistic assessments, an environmental and techno-economic assessment framework (ETEA) is applied to model three MSS treatment scenarios. Each scenario models treatment of MSS by anaerobic digestion (AD) and mechanical dewatering of digested sludge followed by:

- REF: A reference case of storage and arable land application of dewatered digested sludge (DDS)
- ALT1: DDS treatment by Oxypower HTC with Aqua2N nitrogen recovery from process and reject water.
- ALT2: The treatment described by ALT1, followed by hydrochar mono-incineration and Ash2Phos phosphorus extraction.

ETEA is conducted in four stages using data collected from literature and public and private partners. Qualitative and quantitative process flow mapping defines the scenarios and models material and energy flows through the systems. An attributional comparative life cycle analysis (LCA) alongside techno-economic analysis (TEA) follows. The LCA has a gate to grave scope with a functional unit of one ton of total solids treated. Finally, results are evaluated using sensitivity and data uncertainty analysis to identify hotspots and knowledge gaps in the system. Experimental work conducted in tandem with modeling demonstrates a 15% increase in biogas production by applying HTC byproducts to AD to promote biogas production.
Results combining alternative scenarios based on current trends show the potential of emerging technologies to multiply WWTP nitrogen and phosphorus recovery by five and two times respectively, while simultaneously improving net energy recovery by three times. LCA results show reductions of greenhouse gas (GHG) emissions by between 60-70%. Considering emerging MSS technologies from a systems perspective provides critical context that can improve their economic viability. Combining intelligent systems design with these technologies, the models demonstrate how future MSS treatment can provide both good sanitation and recovery of nutrient

and energy resources. Integration of these systems will accelerate the transition from wastewater treatment plants (WWTP) to water resource recovery facilities (WRRF).

Impacts (short presentations)

Evaluation of Per- and Polyfluoroalkyl Substances in Metal Shredder Residue: Preliminary Results

Tuesday, 4th July - 12:00: Impacts (short presentations) (B0.16 KOG)

Erin Bulson [1]***, Christina Remucal*** [2]***, Andrea Hicks*** [2]

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Metal shredder residue is an industrial waste that has been shown to include per- and polyfluoroalkyl substances (PFAS). PFAS are persistent organic pollutants that can bioaccumulate and cause adverse effects on the environment and human health. Metal shredder residue is often landfilled and may be used as alternative daily cover. In the United States, an estimated five to seven million tons of metal shredder residue is landfilled annually. However, the fate of metal shredder residue-derived PFAS in the landfill system remains relatively unknown. Groundwater studies have indicated that PFAS may leach from metal shredder residue and impact groundwater in the absence of an impervious barrier. Therefore, it is reasonable to consider if metal shredder residue-derived PFAS exit the landfill system via leachate or remain sequestered within the landfill system. Yet, at present, there is a significant knowledge gap about the potential mobility and range of concentrations of PFAS within the metal shredder residue waste stream. This information is critical to assess the potential related environmental cycling of PFAS. Recent European studies have started to address these knowledge gaps. A report commissioned by the Dutch National Institute for Public Health and the Environment tracked PFAS freights within the end-of-life vehicles waste stream (a significant subset of metal shredder residue) in the European Economic Area. Similarly, the Norwegian Environmental Agency recently commissioned a study that included the evaluation of PFAS within post-consumer plastics; a limited number of automotive shredder residue samples were analyzed for PFAS. While evaluation of PFAS within the metal shredder residue waste stream is in its infancy, the work presented herein aims to add to a growing body of knowledge with respect to quantity and mobility of PFAS derived from metal shredder residue. Preliminary results of a PFAS leachability study conducted on metal shredder samples from within the United States are presented. Samples were obtained from a variety of sources to account for heterogeneity within the waste stream. The intended audience for this research is industry, government, and the academic community, as these groups work together to address PFAS in recycling and waste streams.

Parametric model for the evaluation of environmental impacts of different earth construction techniques

Tuesday, 4th July - 12:07: Impacts (short presentations) (B0.16 KOG)

Paula HIGUERA [1]

1. *PhD Student*

The challenge for the construction industry in the coming years is to find low environmental impact building solutions. In this context, raw earth construction has experienced a remarkable renaissance in recent decades. However, behind the name “earth material” are hidden many practices that can lead to very different environmental impacts. The analysis of the literature shows in particular an important influence of the use of stabilizing binders (cement, lime), and of the transports whose distances are linked to the origin of the materials, on the indicator of cumulative energy demand. However, this bibliographical analysis does not allow us to conclude on all the environmental impacts. Thus, it appears, on the one hand, important to better understand the design choices influencing environmental impacts, and on the other hand, to produce a generic model allowing designers to choose and evaluate their “customized” construction solutions.

The objective was to develop a systematic parametric model for the life cycle analysis of earthen construction techniques, allowing, on the one hand, a contribution analysis to identify the processes and parameters on which the environmental impacts of earthen construction are based and, on the other hand, a responsibility analysis to identify the actors involved in generating impacts and their levers of action. The whole model, designed on a cradle-to-gate system (use and life cycle not included), allows to compare scenarios in an exhaustive way (more than 5,000 scenarios tested on the four techniques adobe, compressed earth bricks, cob and rammed earth and to identify the appropriate solutions in a given territorial context. The approach also makes it possible to evaluate the amplitude of the variability of the environmental impacts according to the choices of the actors. Many solutions do not allow to obtain better environmental results than the conventional technique with concrete blocks, and this depends mainly on the use of binders and ready-to-use earth, with however nuances according to the techniques. The analysis carried out thus makes it possible to show the ways towards the best strategies of development of the sector to allow an environmental benefit. The modelling of the scenarios, although very complete, must be confronted with professional practices to be enriched, and must also eventually be able to integrate the use and end-of-life phases, but also integrated socio-economic evaluations.

Systematically Assessing Environmental Impacts of Pharmaceuticals - Lessons Learned

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:14: Impacts (short presentations) (B0.16 KOG)

Lowik Pieters [1], *Martijn van Bodegraven* [1], *Rosalie van Zelm* [2]

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Over the life cycle of healthcare processes and products, many emissions and resource extractions occur that can have negative health and environmental effects. If one person is cured today, at the expense of making other people sick tomorrow, healthcare becomes counter-productive. Safe and sustainable pharmaceuticals can contribute to a healthy healthcare system. To understand the environmental consequences of pharmaceuticals, Life Cycle Assessments (LCAs) can provide valuable input. However, it is unclear to what extent pharmaceutical LCAs are representative, reliable and accurate for impact assessment in the healthcare sector.
Therefore, with a literature review on pharmaceutical product LCAs, we aim to present how challenges in performing and interpreting pharmaceutical LCAs can be addressed in the future. Moreover, the review serves to further advance the research field and to come to applicable recommendations for a sustainable healthcare sector.
The work includes 62 LCA studies of pharmaceutical products retrieved through a systematic literature search on Scopus. The studies were analyzed based on the four phases of LCA as described in ISO14040 and 14044 standards: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; 4) interpretation.
Preliminary results showed that key challenges identified in LCAs for pharmaceutical products are:

1. Variations in methodological choices and high case specificity, limiting usability of pharmaceutical LCAs for purposes beyond their stated goal and scope;
2. Limited transparency of the life cycle inventory, hampering our understanding of sources of variability in pharmaceutical LCAs and reproducibility;
3. Impact assessment tends to be limited to Climate Change, whereas impact models on pharmaceutical-specific impacts of toxicity, such as endocrine disruption and antibiotic resistance, are not evaluated.
4. Consistency, completeness and representativeness are difficult to interpret due to missing sensitivity, consistency and completeness analyses.

During the presentation, solutions to address these challenges will be presented.

APPLYING A HYBRID LCA FRAMEWORK TO QUANTIFY CONSTRUCTION PRODUCT CARBON FOOTPRINT IN SUPPORTING LOW-CARBON BUILT-ENVIRONMENT DESIGN: A CASE STUDY OF READY MIX CONCRETE

Tuesday, 4th July - 12:21: Impacts (short presentations) (B0.16 KOG)

Shih-Hsien Yang [1], ***Hoai-Nam TRAN*** [2], ***Han-Ruen Yue*** [1], ***Bo-Kai Chiou*** [3], ***Ching-Wei Yang*** [1]

1. National Cheng Kung University, 2. Duy Tan University, 3. Industrial Technology Research Institute

In Taiwan, National Development Council announced Taiwan's 2050 Net-Zero Emission Path and Strategies roadmap in March to formulate action plans for net-zero transformation policies in the energy, industry, and living areas. Among all the industries, the building and construction industry contributes significant carbon emissions annually. Therefore, quantifying the construction industry's carbon footprint (CF) is essential to Nation's net zero emissions goal. Currently, many low-carbon infrastructure engineering solutions only rely on using low-carbon construction materials. If the material manufacturers cannot supply innovative low-carbon construction products, engineers may face great challenges in delivering low-carbon infrastructure solutions. The reason could be the limited construction products' carbon footprint data available to support civil/ structure engineers in investigating low-carbon engineering solutions. The primary approach to quantifying a product's carbon footprint is by the process-based (PB) life cycle assessment (LCA), which is time-consuming and costly, and solely relies on the product's manufacturers. Indeed, during the infrastructure planning and design, engineers usually do not require or prefer not to use any specific manufacturer's material or product data but adopt public specification data. To achieve the zero carbon infrastructure goal, there is an urgent need to systematically and efficiently quantify CF data for various construction materials of different specifications to support civil/ structure engineers to explore the lowest CF design alternative with satisfactory performance.

This study aims to develop a hybrid LCA framework to quantify the CF of the ready-mix concrete (RMC) of various strength specifications and composition formulations (i.e., fly ash, ground blast-furnace slag) in Taiwan. The Nation's economic input-output matrix was augmented using industrial production and sell inventory statistics from the Ministry of Economic Affairs and job mix formula data of various RMC specifications. The result combines the Nation's energy balance sheet data and energy emission data from the Bureau of Energy to calculate a construction product sector's direct CO_2 emission coefficient (CO_2/\$). The sector's direct CO_2 emission coefficient further multiplies to the Leontief inverse matrix to obtain the product's direct and indirect CO_2 multiplier (CO_2/\$). The RMC's CO_2 multiplier combines with the average RMC price to obtain the cradle-to-gate CF of various RMCs. The results show that the carbon footprint of RMC with the addition of 48% fly ash and furnace stone with the strength of 140kgf/cm^2, 175kgf/cm^2, 210kgf/cm^2, 245kgf/cm2, 280kgf/cm2, 350kgf/cm2, and 420kgf/cm2 are 214 kgCO□e/m3, 227 kgCO□e/m3, 239 kgCO□e/m3, 252 kgCO□e/m3, 265 kgCO□e/m3, 291 kgCO□e/m3, 314 kgCO□e/m3, respectively. Moreover, comparing the CF of RMCs obtained by the hybrid LCA approach proposed in this study and the Taiwan EPA's PB CF database data, the difference is within the 15% range, which is deemed propriety to support civil/ structure engineers during infrastructure project planning and design. Finally, adopting the framework proposed in this study, an average CF of construction products of different specifications can be quickly and systematically quantified. The proposed method can be applied to other countries/regions with compatible data sources to populate its localized construction materials' CF.

On Toast - Environmental Impacts of High-Protein Options for Bread Toppings

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:28: Impacts (short presentations) (B0.16 KOG)

Jessica Bosseaux [1], *Eugene Mohareb* [1], *Cristina Madrid-López* [2]

1. University of Reading, 2. Universitat Autònoma de Barcelona (UAB

Meat production is an important contributor to environmental degradation due to the required resource inputs and their associated climate impact. The reduction in meat consumption and the rise in proportion of people following plant-based diets in the United Kingdom over the last decade is associated with some improvements of environmental emissions and use (Stewart et al., 2021). Nevertheless, this trend must be accelerated towards reaching our collective sustainability targets, such as those highlighted in the EAT-Lancet report (Willett et al., 2019), as well as meeting nutritional expectations and improving public health.

Pulses, particularly beans, are ancestrally consumed due to their climate and disease resilience, nutritional benefits, and ease of storage (Albala, 2017; Popescu & Golubev, 2011). One such pulse is the haricot bean, used in the traditional "beans on toast", which is a common breakfast and snack food in England. Haricot beans, and pulse more broadly, may be a good alternative to other spreadable bread toppings for both the environment and health.

This study investigates the environmental impact of 15 alternatives to beans in tomato sauce that could be considered as a healthy snack and can be spread or deposited on toast. The products have been selected according to their ease to use and their protein content. Serving sizes are also considered to reflect typical practices for their use on bread. Life cycle assessment (LCA) focuses on impacts including water consumption, land use, and global warming potential per serving, using the ReCiPe 2016 midpoint method and the 2020 AGRIBALYSE v 3.1 life cycle inventory. Product flows are revised to reflect UK conditions in place of those in France.

Unsurprisingly, the animal-based products have higher general environmental impacts than plant-based products. Nevertheless, some unexpected results are observed: the four products that had the greatest contribution to climate change are flaked tuna in tomato sauce (0.677 kg CO2 eq/serving), smoked cured ham(0.505 kg CO2 eq/serving), sardine in tomato sauce (0.310 kg CO2 eq/serving) and salmon rillette (0.301 kg CO2 eq/serving), revealing the relatively high impacts of commercial fishing. This is due to diesel combustion in marine engines and the necessary cold chain, including in transport and storage conditions.

Concerning water consumption, peanut butter production (0.0073 m^3/serving) was found to be higher than soft cheese, half of the meat alternatives, and all of the fish alternatives; this is due to irrigation requirements at peanut farms as well as at sugar beet farms, a secondary ingredient in peanut butter. It is followed by flaked tuna in tomato sauce (0.006 m^3/serving) and the traditional haricot beans in tomato sauce (0.006 m^3/serving). Also, land use for peanut butter (0.202 m^2a crop eq/serving) is higher than soft cheese (0.153 m^2a crop eq/serving) but remains lower than all meat-based alternatives. When normalising these impacts based on protein-corrected amino acid score, the order doesn't change substantially, with beans on toast being top of the list.

Haricot beans in tomato sauce shows interesting nutritional benefits as a high source of both carbs and protein, while being low in fat. The volume of the portions is higher and show a better calorie density, which may lead to the use of one single portion of beans, while the high calorie density products such as cheese may lead to the consumption of several recommended portions.

Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 2)

Comparative assessment of national indicator system towards a circular economy in Japan, China, the EU, and individual EU countries

Wednesday, 5th July - 09:00: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 2) (A0.51 KOG)

Chika Aoki-Suzuki [1], *Seiji Hashimoto* [2]

1. Institute for Global Environmental Strategies, 2. Ritsumeikan University

Countries which have developed national-level resource efficiency (RE) and circular economy (CE) strategies are increasing both in Europe and, more recently, in the Asian region. RP and various material flow indicators, as well as recycling rates, have been used for monitoring and assessment of policies on RE&CE in Japan, the European Union (hereafter EU) and individual EU countries. In addition, recent developments in RE&CE policies have prompted countries to establish new indicators for national strategies, and for their assessment and monitoring. Meanwhile, the international community has emphasized the importance of concerted efforts regarding RE&CE indicators and metrics for measuring progress at forums related to the SDGs, G7 and G20 processes .

In this study, we review RE&CE-related indicators from Japan, China, the EU, and EU individual countries, which have developed national-level RE&CE plans and indicators. We classify the reviewed indicators into two viewpoints of ten categories; environmental viewpoints (six stages of material life cycle and other environmental impacts) and socio-economic viewpoints (social, economic and RP). The six stages include natural resource input, raw material input into production, raw material utilization in production processes, product use, end of life product treatment and waste disposal into the environment. We then analyze commonalities and differences in terms of the indicators, and also examine the relevance of each indicator set to the policy purpose.

We found the following points as a result of the review. Many of the reviewed countries are aiming at a low-carbon and resource-efficient society and are looking to strengthen their industrial competitiveness through a CE in their policies . The RP indicator is the core indicator for most reviewed countries. The resource input material flow indicator, material footprint/raw material equivalent material flow indicator (and the indicator on the use of recycled material such as circular material use rate, are common among the reviewed countries. No indicators on by-product use or material stocks were found. It was also found that indicators on product use are diverse. For example, reuse, repair and sharing-related indicators as well as environmentally conscious products, labelling and green procurement indicators have been set in some countries. Recycling rates including one for specific materials and waste disposal are common indicators. However there could be concerns in terms of the differences in definition and metrics. The focus on CE approaches rather than recycling is relatively weak. For other relevant environmental impacts in many reviewed countries, climate/energy related indicators are common which is aligned with the increased attention to the linkage with CE and climate change. However, no indicators have been found which directly addresses the climate impact through CE. It is also observed that indicators linking with other environmental impacts, including biodiversity loss, are not well established yet. Thus, in general, the national indicator system is well established for resource-decoupling assessment, but is not sufficient for impact decoupling assessment.

As for socio-economic indicators, the industry size of CE business and employment are common indicators, suggesting that the reviewed country is interested in developing a domestic recycling industry and thus, this is also shown in their policies.

While we found some commonalities in indicator selection, indicator sets among countries are still diverse and international comparability on metrics still remain a challenge.

Assessing circular economy's compatibility with 'sustainable work'

Wednesday, 5th July - 09:15: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 2) (A0.51 KOG)

Anran Luo [1]

1. Helmholtz Centre for Environmental Research

(How) Can we conceptualize 'sustainable work' in a socially and environmentally friendly circular economy (CE)? CE envisions a future of sustainable production and consumption, and has gained momentum in European and German policy agendas as a transformative concept to reduce virgin material extraction and waste. High-technology innovations in digitalization and artificial intelligence have been espoused to be central to CE's means of transformation, yet their relationship to the 'future of work' is contested and uncertain (Clube 2022). Assuming the economy is embedded within society and the environment (Göpel 2016), whether CE can fulfill its environmental targets is highly dependent on the unfolding dynamics between socioeconomic systems and their agents (Zink and Geyer 2017).

Dominant narratives of the CE showcase that environmental benefits of the CE is pre-conditioned on its ability to bring economic and social benefits (Leipold 2021; Luo et al. 2021). However, while studies scrutinize the economic and environmental potentials and barriers of CE ambitions, studies addressing the social dimensions mostly point out what is lacking or under-addressed (Clube & Tennant 2020; Moreau et al. 2017; Ghisellini et al. 2016). Scholarship is emerging on the social dimensions of CE and sustainable consumption (Hobson et al. 2021), but CE and sustainable production has primarily been studied from perspectives of materials flow (Winans et al. 2017), eco-efficiency (Korhonen et al 2018) and technology (e.g. Avanthi & Mohan 2022), largely neglecting social elements of production. CE literature that directly address CE and work interpret 'work' primarily as quantity of jobs (Chateau & Mavroeidi 2020; Padilla-Rivera et al. 2020), with a minority taking the quality of jobs into consideration (e.g. Laubinger et al. 2020; Clube and Tennant 2020).

Outside of CE studies, the link between sustainability and 'work' or 'labour' has been investigated in heterodox schools of economics (e.g. feminist economics: Biesecker & Hofmeister 2010; Dengler & Lang 2022), sociology (Hoffman & Paulsen 2020), human geography (Bouzarovski 2022), and political ecology (Coe 2021). However, these strands of scholarship seldom cross-pollinate and the conceptualization of 'sustainable work' remains fragmented.

To address this research gap, this paper will first review the state-of-the-art of existing knowledge on 'sustainability' and 'work' at the macro-level, followed by an analysis of whether and how scholarly conceptualizations of 'sustainable work' (mis)align with CE at the macro-level (whole economy). This review will serve as a foundation for further research into co-production of interventions that enable 'sustainable futures of work' in specific CE sectors e.g. chemicals industry (meso-level).

Abstract for Special Session *Assessing Progress Towards a Sustainable Circular Economy Across Scales*

How can a city get circular? Comprehensively Monitoring Urban Circularity and Deriving Policy-Relevant Indicators. The case of Vienna, Austria.

Wednesday, 5th July - 09:30: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 2) (A0.51 KOG)

Nina Eisenmenger [1], ***Christian Dorninger*** [1], ***Willi Haas*** [2], ***Andreas Mayer*** [1], ***Lisa Kaufmann*** [1], ***André Baumgart*** [3], ***Dominik Wiedenhofer*** [1]

***1.** University of Natural Resources and Life Sciences, Vienna (BOKU), **2.** University of Natural Resources and Life Sciences, Vienna, **3.** Institute of Social Ecology (SEC), University of Natural Resouces and Life Sciences, Vienna*

The city of Vienna published the Smart City Vienna Framework Strategy (SCVR) in 2019 (revised in 2022) and therein placed the issue of resource conservation and dematerialization very prominently as one of three overall visions (the other two being quality of life and innovation). The following resource use targets are defined (target year 2030): GHG emissions -50%, energy consumption -30%, and material footprint -30%. Among the thematic field “zero waste & circular economy” further targets are defined: reduction of food waste (-50%), increase of recycling rate to 60%, and 100% recycling of non-avoidable waste. Looking at these ambitious and pioneering goals, two questions arise: (1) how does Vienna currently perform in terms of material use? (2) How can circularity be defined and measured on the city level and for Vienna in particular? In the project MOCAM funded by the city of Vienna, we provided a first assessment of Vienna’s social metabolism by calculating the material use (domestic material consumption, DMC) and material footprint of Vienna for 2010 and 2019 following standard economy-wide material flow accounting methods[1,2]. In a follow-up project VICE, we currently perform a circularity assessment following the circular economy framework of Haas et al.[3,4] and Mayer et al.[5]. The calculation of material flow indicators for Vienna, implementing the urban metabolism approach[6–10], was challenging due to the lack of trade data. Consequently, we used two different approaches to compile MFA data: in a bottom-up approach we firstly summed up detailed data for material intensive hotspot sectors (construction, mobility, nutrition, waste management, tourism, heath care). Secondly, we applied a top-down approach implementing a systemic perspective on the city using a combination of input-output modelling and consumption expenditure data. The two approaches delivered different results that spanned a range in which the actual results are to be expected: the material footprint of Vienna for 2019 is between 10 t/cap/a (bottom-up approach) and 17 t/cap/a (top-down approach).

Research on an economy-wide circular economy (CE) analysis developed fast during the past decade providing macroeconomic CE indicators and empirical analysis[3–5] mainly applied to the national level. An application at the urban level is subject of ongoing academic research and has to conceptually consider the particular characteristics of a city, i.e. little extraction and production, but high consumption activity, and therefore a very limited potential for closing material cycles[11,12]. In our project VICE, we currently compile material flows to and within Vienna differentiating material and energetic uses as well as accumulation in physical stocks, and end of life wastes derived from socioeconomic activities going to waste treatment. All material flows are mass balanced and differentiate types of materials as well as societal uses in accordance with policy issues. The circularity rate of Vienna (also implemented as circular material use rate, see Eurostat) is calculated as recycled material as a fraction of total material inputs (processed materials). Taking the urban characteristics into account, we differentiated three different scale levels: circularity of Vienna from a strict territorial perspective, regional circularity considering the urban hinterland and recycling activities therein, and a circularity potential under application of average Austrian recycling rates for the most relevant material flows.

Towards a system-wide and consistent understanding of material use in product- and sectoral stocks – insights from economy-wide, dynamic material flow analysis

Wednesday, 5th July - 09:45: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 2) (A0.51 KOG)

Jan Streeck [1], Hanspeter Wieland [1], Helmut Haberl [1], Fridolin Krausmann [1], Barbara Plank [2], Stefan Pauliuk [3], Dominik Wiedenhofer [1]

1. *University of Natural Resources and Life Sciences, Vienna,* **2.** *University of Natural Resources and Life Sciences, Vienna.,* **3.** *Freiburg University*

To evaluate the sustainability of the circular economy (CE), models need to take a system-wide perspective that detects burden shifts along and between supply-chains (e.g., the construction of net-zero emission buildings shifting GHG emissions from the use to the production phase; the re-use of building parts or materials potentially inducing increased transport emissions). On top of full system coverage, CE assessments need to include a minimum level of detail to, first, adequately model the lifetime, recycling potential and technological development of products, and second, to evaluate the link of resource use to human well-being. For this, knowledge on the end-use of materials in product or sectoral stocks is required, as only then product-specific model details can be assigned, and a meaningful connection of material use to the functions and services for human well-being can be made (e.g. linking steel use in a building to the floorspace provided). With this information, the coupling of service provision to resource use can be assessed for historical periods, together with the CE options to make this link more resource-light in the future.
The toolbox of dynamic material flow analysis (MFA) is suited to evaluate the CE and the resource-service link as shown by many recent applications. However, the current state of the two major MFA methods has yet to integrate a system-wide with a detailed perspective. The method of stock-driven MFA is successful in quantifying material use in important end-use sectors like buildings and motor vehicles, often including great technological detail. However, available assessments are often limited to the mentioned sectors due to the large efforts and lacking data to cover economy-wide end-use applications. In contrast, the method of inflow-driven (economy-wide) MFA starts out from an economy-wide perspective, which by default encompasses all end-use applications. However, this method draws on statistics which lack information on end-use distinction and usually only allows for estimating material flows and stocks for one aggregate end-use total. Recent advances in inflow-driven MFA introduce coarse end-use sectors to economy-wide MFA, but sector distinction remains largely uncertain and conflicting.
Here we present efforts to quantify economy-wide material stocks and flows in broad end-use sectors via inflow-driven MFA, based on a recently compiled material flow dataset that covers 14 materials, 177 countries and the years 1900-2016. The presentation focuses on the data sources and methodological options to introduce end-use information to these economy-wide material flow data, drawing on statistics of industry shipments in physical units, and the multi-regional input-output databases EXIOBASE and GLORIA. We present apparent mismatches between physical and monetary data sources and discuss the resulting large uncertainty of introducing end-uses to aggregate material flows. Furthermore, we describe additional efforts to improve and validate end-use allocations (e.g. comparison to auxiliary statistics and stock-driven MFA estimates) and in how far these can reduce uncertainty. In closing, we discuss potentials for a further integration of industrial ecology methods (i.e. stock-driven and inflow-driven MFA, input-output analysis) to improve result validity and resolution, and to enable system-wide assessments of a sustainable circular economy. SUBMISSION TO SPECIAL SESSION: ‘Assessing Progress towards a sustainable circular economy across scales’

Circularity strategies for the provision of goods and services, and their synergies and trade-offs with climate change mitigation

Wednesday, 5th July - 10:00: Special Session: Assessing Progress Towards a Sustainable Circular Economy Across Scales (Part 2) (A0.51 KOG)

Eugénie Joltreau [1], *Elena Verdolini* [1], *Cristina Cattaneo* [1]

1. Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (EIEE/CMCC)

To limit global warming to 1.5°C, decarbonizing the industry will be critical. Several options are put forward by the IPCC to reach net zero in the industry: energy efficiency, carbon capture and storage/utilization (CCS/CCU), material efficiency (ME), and circular economy (CE) strategies (IPCC, 2022). On material efficiency and the circular economy, the report advocates for transforming the industry through innovative circular business models along the value chain. The contribution of material efficiency and circular economy in climate mitigation could be extensive (IPCC, 2022). For example, according to Material Economics (2019), the contribution of circularity for net zero pathways could be up to 27% for steel and plastics and up to 44% for cement.

Despite this substantial potentials, there are several aspects that deserve further inspection. These range from conceptual clarifications of the overlaps and similarities between material efficiency, circularity, and emissions mitigation options. More generally, a key aspect that needs a better understanding is that of synergies and trade-offs between industrial circular strategies and policies with climate mitigation (IPCC, 2022). In particular, the mechanisms by which 'circular' strategies result in emission reductions are unclear. While environmental impacts of secondary materials are usually much lower compared to primary materials (IPCC, 2022), a common mistake is to assume that fostering circularity and recycling will homogeneously translate to macro-level environmental benefits, e.g., a circular rebound effect (Zink and Geyer, 2017). Previous work, e.g. by Cantzler et al. (2020), provides a first review of synergies between circularity options and climate change mitigation, and find that most studies analyze incremental measures claiming, but not demonstrating emission mitigation. Furthermore, basic materials' sector are often treated separately from the corresponding end-use sectors and final demand pathways (e.g., transport, infrastructure). We herein therefore aim to address how the circular economy affects value chains upstream and downstream from the firms and industries implementing circularity strategies.

Given the limitations in research related to circular economy, the contribution of our paper is as follows.

We review the literature and develop an overarching definition; particularly, regarding micro-circular strategy, a circular relation, circular economy policies, and material efficiency. Enterprises may undertake resource-saving actions ('circular strategy') by establishing backward relations on their own (circular model) or through organized markets, often with the help of circular policies. We then review in detail the synergies and trade-offs between micro-level circularity, circular policies and overall climate change mitigation.

In our work, we classify the main circular economy policies and reviews the literature on the effectiveness of these policies. Then, this paper provides a conceptual framework to evaluate circular options and policies, and climate mitigation. In particular, we reflect on how micro-circular strategies relate to each other in the value chain and what physical outcome they could produce at a more aggregate level (macro modeling level). In addition, it allows us to establish basic theoretical conditions that allow us to analyze mitigation claims from the literature. Following this framework, this paper describes how the industry is linked to end sectors in terms of material flow (value chain analysis). We focus on three materials (plastics, cement, steel) and three end sectors (packaging, building, transport). Focusing on this intersection of the value chain, we review the literature on the synergies between CE strategies and climate change mitigation.

Interested by the proposed special session "Assessing progress towards a sustainable circular economy…"

Special Session:
Secondary Raw material recovery and impacts

Waste flows and environmental impacts in Life Cycle Assessment: A macro-scale application of the WasteFootprint Python tool.

Wednesday, 5th July - 09:00: Special Session: Secondary Raw material recovery and impacts (C1.31 KOG)

Stewart Charles McDowall [1], ***Elizabeth Lanphere*** [1], ***Carlos Felipe Blanco*** [1], ***Stefano Cucurachi*** [1]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden

In the imperative pursuit of achieving sustainability objectives and curtailing our environmental footprint within planetary boundaries, the development of a ‘circular economy’ has become a critical area of focus. Fundamental to this development is the reduction of life cycle waste through the implementation of ‘re-X’ strategies (e.g., design for repair, remanufacture and recycling) (European Union, 2022). To reduce environmental damage and improve supply chain resilience, product and process design must be extensively improved and the secondary-raw-material recovery system expanded.

Life Cycle Assessment (LCA) is a useful method for the estimation of holistic impacts of products and processes. There is, however, a conspicuous gap in the understanding of the waste footprint of human activities and their relationship with environmental damage (Laurenti et al., 2023). Conventional LCAs consider waste as a ‘service’ (Guinée & Heijungs, 2021), and typically use generic waste processing models (Beylot et al., 2018) that break the causal link between the functional unit and the waste-associated impacts.

Lacking an indicator at the impact assessment level, LCA studies can provide only scarce information regarding the impacts of waste, and none concerning hot-spots in the product system and the wider economy, whose amelioration plays a vital role in the quest toward circularity.

To better assess waste flows and their impacts, the authors have developed a Python tool designed to track them in LCA by translating such exchanges into impact categories (Lanphear et al., 2023). While methods with similar aims exist (FOEN (ed.)., 2021; Laurenti et al., 2023), they either lack specificity, or suffer from errors due to multiple counting.

This study offers a macro-scale waste footprint analysis based on the application of the WasteFootprint tool, considering ~1500 representative activities from the EcoInvent 3.9 ‘cut-off’ LCA database that were selected similarly to Laurenti (2023). The data presented are sector- and product-specific assessments of waste exchanges, demonstrating their sources, endpoints, and aggregations, and highlighting waste hot-spots at the level of sectors, products, and supply chain sub-processes.

Additional to the waste footprint results, this analysis showed that waste flows in the supply chains of most products are very poorly categorised (<5%) and that increased categorisation is proportional to the hazardousness of the waste footprint for most products (excluding the agricultural sector). Further, the LCA results from a range of standard environmental impact methods exhibited correlations to an activity’s waste footprint, suggesting that reducing life cycle waste could be an effective way of reducing environmental harm.

Though often defined and dismissed as “a material with a negative economic value” (Guinée et al., 2004), waste is a nebulous concept, poorly delineated and variable across space and time. Moreover, from a systems perspective, the notion of waste is anathema to the circular economy, and it is far more useful to consider the identity and nature of the specific material flows. Thus, precise and detailed categorisation of these is essential to understand the ’circularity’ of an activity as well as its life cycle externalities.

This macro-scale study demonstrates the potential of the WasteFootprint tool for LCA to provide valuable information for product design, supply chain management, and policymaking. The results can provide insights into the circularity of a given product and may illuminate new strategies for environmental impact reduction. For its full utility to be actualised, however, improvements in the underlying waste flow data are essential.

Figures,references&code:
https://leidenuniv1-my.sharepoint.com/:f:/r/personal/mcdowallsc_vuw_leidenuniv_nl/Documents/CML/StewPhD_shared/ISIE_s

Sustainable Neodymium Recycling for Energy Transition: Insights from the SUSMAGPRO Project

Wednesday, 5th July - 09:15: Special Session: Secondary Raw material recovery and impacts (C1.31 KOG)

Brenda Miranda Xicotencatl [1], ***Sander van Nielen*** [1], ***René Kleijn*** [1]

1. *Leiden University, CML*

Due to the increasing adoption of wind turbines and electric motors for battery-electric mobility, the energy transition requires an increasingly secure supply of permanent rare earth magnets. While the current supply chain of rare earths heavily relies on mining them in China, neodymium recycling outside of China is expected to play a prominent role in the future. One of the alternative recycling processes currently under development in the Horizon 2020 project "SUSMAGPRO" involves using hydrogen to retrieve Nd-Fe-B from end-of-life magnets. Within SUSMAGPRO, technology developers are testing pilot plants and defining processing routes, starting from various sources of post-consumer magnetic scrap, with several types of magnets as potential products. To support the technology developers through this wide solution space, we planned a sustainability assessment in three stages. In the first stage, we quantified neodymium waste in European countries using material flow analysis. We also performed a prospective life cycle assessment on the primary production of Nd-Fe-B magnets. In the second stage, we performed an LCA of the recycling systems at their current scales (lab or pilot). We then identified hotspots and defined a set of upscaling and optimization parameters. The third stage consisted of integrating the knowledge of the two previous stages and evaluating the most promising routes in upscaled scenarios projected into the future, considering future trends in the energy systems up to 2050.

Our results showed that the hydrogen-based recycling of magnets at industrial scale would perform better than the primary production at industrial scale in many impact categories. One of the key drivers of this difference is the reduced energy demand from reprocessing the alloy instead of chemically reducing the metallic oxide extracted from the ore. The advantage of the hydrogen-based recycling alternative over the primary production incumbent is expected to become even more pronounced in the future as energy systems become less environmentally impactful.

The iterative process involved scenario workshops and expert consultations. The sustainability assessment, also including the assessment of prospective economic and social factors, will be concluded by the end of the project, in 2023. The lessons learned during the research project can be extended to other projects developing emergent technologies for the energy transition. Our case study illustrates the importance of reaching technology developers along the supply chain at early stages of the technology development with a systems perspective. It also outlines challenges and opportunities when fostering collaborations beyond the project consortium.

Techno-economic-environmental categorization of secondary raw material production processes

Wednesday, 5th July - 09:30: Special Session: Secondary Raw material recovery and impacts (C1.31 KOG)

Martin Hillenbrand [1], ***Christoph Helbig*** [1]

1. Ecological Resource Technology, University of Bayreuth, Bayreuth, Germany

Because of our society's dependence on metal resources, there is a growing concern about the impact of potential shortages of these resources, both for current and future generations. To meet the increasing demand for resources, the share of secondary production, especially for critical raw materials, must increase to limit the need for virgin materials. There is a limited understanding of what boundaries and new resource scarcity situations emerge with a higher secondary share in the total supply chain. Our understanding of the interrelationships of the various processes and technologies must be improved to realize the full potential of the circular economy in a stable and risk-minimizing manner. Therefore it is crucial to identify which processes are critical and why.

The criticality and scarcity assessment of primary materials is done via different evaluation schemes. However, previous criticality studies focused mainly on the material itself. Recycling was considered exclusively by the four categories end-of-life recycling rate, recycled content ratio, recyclability, and end-of-life recycling input rate [Helbig et al. 2021, Resources 10(8), 79].

Those categories do not adequately describe the criticality situation of materials with a high recycling share, particularly metals. A systematic overview of existing secondary material production processes and their interrelations is needed to identify potential high-risk areas and lower systematic risks of secondary production. We present a comprehensive overview of recycling processes and a categorization scheme based on technological, environmental, and economic evaluation criteria. The overview covers a wide range of recycling processes, from traditional methods like mechanical recycling to newer processes like bio-based and chemical recycling. The categories include factors for the process inputs and outputs, the application of the process, and categories describing the process itself. By applying these criteria to various recycling processes, we aim to identify best practices and areas for improvement.

This overview of different recycling processes was the starting point for a broader discussion of secondary critical raw material supply pathways and their associated criticalities. We want to present the current findings for the investigated processes for different material flows and discuss their significance for the future of secondary production. A first assessment of the criticality of exemplary recycling processes shall be discussed, and the potential for methodological improvement will be highlighted.

By identifying the most promising recycling processes and improving the less effective ones, we can take a step towards realizing the full potential of recycling efforts and ensuring a sustainable future. The obtained information can be used in the future to carry out material flow analysis that considers recycling flows in a more realistic and detailed way, with the ability to model different secondary production scenarios.

In conclusion, recycling critical raw materials is a crucial issue requiring a multi-disciplinary approach. By presenting a comprehensive overview of recycling processes and a categorization scheme based on technological, techno-environmental, and techno-economic criteria, we hope to contribute to the broader discussion of secondary critical raw material supply pathways, stabilize the availability, and raise the resilience of secondary production services for our society in total.

The results of this study will help design materials and policies for higher circularity of critical raw materials and ensure a sustainable future.

Developing a Model for Evaluating the Role of Refining Technologies in Increasing High-Value Recycling of End-of-Life Aluminum Scrap

Wednesday, 5th July - 09:45: Special Session: Secondary Raw material recovery and impacts (C1.31 KOG)

Alissa Tsai [1], ***Yongxian Zhu*** [1], ***Seyed Heidari*** [1], ***Daniel Cooper*** [1]

***1.** University of Michigan*

Nearly a quarter of global greenhouse gas emissions are attributable to industry, where material production is the dominant source of emissions. Of the major industrial materials, aluminum is seeing the most rapid increase in demand and is the most energy-intensive (per unit output) to produce from natural resources. The aluminum sector must decarbonize; however, there are limited opportunities for further improvements in the energy efficiency of primary production. Furthermore, switching to renewable energy for primary aluminum production lowers carbon emissions but does not mitigate the harmful environmental effects of bauxite residue (red mud) and alumina smelting pollution. On the other hand, aluminum recycling requires only around one-tenth of the energy of primary production and there is great scope for increasing aluminum recycling with domestic U.S. end-of-life aluminum recycling rates only around 45%. Industry decarbonization pathways require >90% recycling rates by 2050 as a necessary but not sufficient condition for meeting the 2°C warming target. However, there are technical barriers to increasing the recycling rate due to the compositional mismatch between the chemistry of the scrap streams available for recycling and the chemistries of the alloys demanded by industry to make new products. This mismatch can arise from alloy mixing at end-of-life, contamination with foreign elements, and shifting alloy demand. Perfect separation of end-of-life material is unlikely to be economically viable and does not address the mismatch from changing alloy demand. A potential solution to correct compositional mismatch is the use of in-melt refining technologies such as fractional crystallization, fluxing, low temperature electrolysis, vacuum distillation, electro-refining, and membrane purification. This study investigates the technical potential of these refining technologies, with a focus on fractional crystallization, to overcome the compositional mismatch barrier and increase domestic U.S. aluminum recycling rates, reducing industry emissions.

The improvement in U.S. aluminum recycling rates and emissions through refining technologies is determined through a Python-based linear optimization framework. This optimization model aggregates supplied data on the quantities and compositions of available scrap streams and alloy products to minimize the embodied energy required in alloy production to meet the product demand specifications. The quantity and composition of the annual new alloy demand are determined using dynamic material flow analysis (DMFA) and the Teal sheet composition limits respectively. Quantities and compositions of the annual scrap streams are similarly determined using the DMFA coupled with recycling system modeling. To model the aluminum scrap refined using fractional crystallization, processed scrap stream compositions are estimated through solidification simulations using Thermo-Calc, a leading CALPHAD (CALculation of PHAse Diagrams) software package. The robustness of the optimization results to the inevitable system uncertainties are examined using an extensive sensitivity analysis. In this talk, we will present the results of the optimization model with fractional crystallization as a preliminary test case and conclude with a discussion on the potential of using the framework to model alternative refining technologies such as fluxing, vacuum distillation, and membrane purification to reduce compositional mismatch between scrap aluminum and alloy products.

The regional circularity of zinc - A dynamic MFA approach

Wednesday, 5th July - 10:00: Special Session: Secondary Raw material recovery and impacts (C1.31 KOG)

Leon Rostek [1]***, Antonia Loibl*** [1]

1. Fraunhofer Institute for System and Innovation Research ISI

For currently ongoing discussions regarding circularity and improved sustainability of resource use, resource management is indispensable. This requires a quantitative description of anthropogenic material cycles. The quantification of material flows allows for analysing the circular performance of materials, finding potentials to safe resources and tracking efforts towards a circular economy over time. In a former study, we developed a dynamic and retrospective material flow model of the global zinc cycle. The study is published in Resources, Conservation and Recycling (Rostek et al. 2022) and shows, that the circular performance of the base metal zinc still has considerable potentials for improvements. Our analysis shows that major zinc losses occur in the collection of post-consumer wastes and in steel recycling processes where zinc from galvanized scrap goes into steelmaking dusts.

Many studies showed extensive regional disparities regarding material systems. Furthermore, unused potentials need to be addressed by targeted policy and innovation efforts, which are organised on regional level. Therefore, it is valuable to expand and model regional zinc flows and stock beside the existing global quantification. We developed MFA models covering the world regions China, Europe, North America, Latin America and Asia (besides China). The modelling approach is top-down, inflow driven and dynamic. Each of the models covers the overall anthropogenic zinc cycle within its respective spatial boundaries including the life cycle phases mining, metallurgy, intermediates production, finished goods manufacturing, use phase, waste processing and recycling. The regions are interconnected via foreign trade flows of manifold goods reaching from ores over high-grade metal and end use products to scraps. An extensive zinc trade network quantification, presented at the ISIE SEM section conference 2022 in Vienna, is applied. While doing so, we maintain the overall mass balance. The closed mass balance, bottom-up validations and expert consultations ensure the quality of the model outputs. Nevertheless, a part of the required exogenous variables like the product lifetimes or the exact end use distribution is characterised by lower data availability, especially on regional level. This leads to unavoidable uncertainties, which we address through sensitivity analysis.

Within the proposed presentation, we will show the stock dynamics of the different regions, namely the quantity, growth dynamics, saturation levels and a comparison of stock per capita. We compare the recycling activities, including the efficiency of collection and separation of waste as well as the different recycling pathways. Recycling indicators like the recycling input rate or the end of life recycling rate enable to compare the recycling performance of regions with different size and level of development. Finally, we will discuss recommendations for actions towards closed regional zinc cycles. These include the implementation of recycling technologies tailored to secondary raw material stocks and flows of specific regions, as well as regulatory measures to reduce existing regional barriers towards higher circularity of zinc.

Reference:

Rostek, L.; Tercero Espinoza, L. A.; Goldmann, D.; Loibl, A. (2022): A dynamic material flow analysis of the global anthropogenic zinc cycle: Providing a quantitative basis for circularity discussions. In: Resources, Conservation and Recycling, 180, p. 106154.

Evaluating the costs and benefits of using recycled aggregate concrete in buildings: Does recycling lead to long-term sustainability for sure?

Wednesday, 5th July - 10:15: Special Session: Secondary Raw material recovery and impacts (C1.31 KOG)

***Xiang Xie* [1], *Haoyu Huang* [1]**

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Concrete is a versatile material widely used in the construction industry for centuries. With the growing investment in this sector, about 30 billion tons of concrete are produced each year, responsible for at least 8% of the world's carbon emissions. Meanwhile, the surging amount of waste generated by the construction industry, known as Construction and Demolition (C&D) waste, becomes a significant threat to the environment. To accelerate the sustainable agenda, Recycled Aggregates (RAs), processed by C&D waste recycling plants, are reused in concrete production to reduce the depletion of Natural Aggregate (NA) sources, thus contributing to the circular economy in construction. Several studies have been conducted to assess the life cycle impact of adopting RA on reducing carbon emissions for concrete production, taking into account factors, such as the Recycled Aggregate Concrete (RAC) mixture design, carbon dioxide uptake, and transportation of RAs. However, in addition to the Life Cycle Assessment (LCA) at a macro or national level for concrete production, it is also important to assess the impact of using RAC on individual buildings at a micro or local level. On the one hand, compared with NAs, RAs are more porous and less dense due to the mortar adhering to their surface, and the compromised mechanical performance shortens the service life of structures with RAC. Furthermore, the chloride resistance of RAC is relatively low, not sufficient to protect reinforcing steel from corrosion. As a result, the additional embodied carbon from extra repair and maintenance or due to reduced building lifespan needs to be considered. On the other hand, most of the recycled concrete is applied to building envelope components. The thermal resistivity and capacity of RAC increase with an increase in the replacement ratio of recycled aggregate, particularly coarse aggregate. It is the two sides of the same coin. Although energy-saving in hot climates, in cooler climates such as the UK, buildings with high thermal capacity require more energy for heating and increase carbon footprint due to the combined heating loading required from the envelope and the internal spaces. This paper provides a life cycle assessment framework for evaluating the whole life carbon footprint variation when using RAC in buildings. Besides the reduced embodied carbon from recycled raw materials, the stochastic service life model is established to estimate the time to corrosion-induced cracking and additional embodied carbon from repair actions or equivalently from the shortened lifespan is calculated. Moreover, the Cambridge Housing Model (CHM) is utilised in this framework to model the energy demand and corresponding operational carbon, subject to the modified thermal resistance of the envelope because of the use of RAC in English residential buildings. Beyond the immediate and most noticeable reduction of embodied carbon from concrete production, the LCA framework for evaluating the whole life carbon footprint of individual residential buildings gives a fair and long-term judgement on the costs and benefits of using RAC in buildings. In future work, the change of climate for England due to global warming and the decarbonisation of the UK electricity supply will be incorporated into the framework to give more accurate suggestions on RAC usage in buildings.

Special Session: Transition towards Sustainable Agri-Food systems: Can Financial Incentives Steer Dietary Behavior?

True Cost Accounting of organic and conventional food production

Wednesday, 5th July - 09:00: Special Session: Transition towards Sustainable Agri-Food systems: Can Financial Incentives Steer Dietary Behavior? (A1.44 KOG)

***Amelie Michalke* [1], *Sandra Köhler* [2], *Lukas Messmann* [2], *Andrea Thorenz* [2], *Axel Tuma* [3], *Tobias Gaugler* [4]**

***1.** University of Greifswald, **2.** Resource Lab / Center for Climate Resilience – Augsburg University, Germany, **3.** Chair for Production & Supply Chain Management – Augsburg University, Germany, **4.** Technische Hochschule Nürnberg*

Agricultural activities are one of the biggest polluters globally. Emissions of greenhouse gases, nitrogen, or the use of ecotoxic fertilizers and pesticides put pressure on both adjacent and global ecosystems and societies. Organic production practices are widely seen as one pathway towards more sustainable agri-food systems, as the magnitude of environmental impact caused can vary drastically between agricultural practices. However, current market prices do not reflect social and environmental damage caused by the production of foodstuff. Consumers are misled towards demand of unsustainable and inadequately priced foodstuff by an insufficient internalization of externalities. This work evaluates environmental damages economically: in a True Cost Accounting (TCA) case study on 22 German agricultural products, we link environmental assessments of organically and conventionally produced foodstuff with approaches for monetizing environmental impacts. First, based on the AgriFootprint 5.0 database, we conduct Life Cycle Assessments (LCA) of all 22 products to calculate environmental impacts on the level of 18 LCIA impact categories of the ReCiPe 2016 method. In particular, we model and explore differences between organic and conventional production practices and between food categories (plant-based, animal-based, and meat). Second, midpoint values are monetized with state-of-the-art costing factors to calculate external costs of each product. A comparison of true costs (market prices plus external costs) with current market prices allows for a discussion on unsustainable dietary choices due to uninternalized externalities. We find that, on average, plant-based production has external costs of €0.79 per kg for conventional and €0.42 for organic products. Conventional and organic milk and eggs induce external costs of, on average, €1.29 per kg and €1.10 per kg, respectively. Conventional meat causes externalities of €4.42 and organic meat about €4.22 per kg, with beef generating the highest costs of all. Especially for plants, environmental favorability of organic production is confirmed but resulting organic market prices after internalization still exceed conventional prices, underlining that current pricing levels of foodstuff are inadequate in terms of the "polluter-pays" principle. Additionally, the results reveal a major impact of dietary behavior. Meat and dairy-based foodstuff lead to considerably higher externalities than plant-based foodstuff, regardless of the production method. This notion is understandable, as process chains of livestock are complex and require more resources and consequentially more emissions than plant production. Therefore, consumers' dietary behavior should transition towards a more plant-focused diet, which could be induced by internalizing external costs into market prices that would disproportionately penalize animal-based products – contributing to the sustainable development goals and also yielding health benefits for consumers.

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Please note: This submission is ideally part of the special session "Transition towards sustainable Agri-Food-Systems: Can financial incentives steer dietary behavior?" (proposed by Amelie MICHALKE, Lukas MESSMANN, and myself). In case the special session proposal is rejected, I am of course happy to have this talk assigned to another session.

Customers' behavior towards true prices of food: lessons learnt from informational campaigning and factual intervention

Wednesday, 5th July - 09:15: Special Session: Transition towards Sustainable Agri-Food systems: Can Financial Incentives Steer Dietary Behavior? (A1.44 KOG)

Amelie Michalke [1], ***Christoph Semken*** [2], ***Lennart Stein*** [1], ***Tobias Gaugler*** [3]

1. *University of Greifswald*, **2.** *Universitat Pompeu Fabra*, **3.** *Technische Hochschule Nürnberg*

Please note: This submission is ideally part of the special session "Transition towards sustainable Agri-Food-Systems: Can financial incentives steer dietary behavior?" (proposed by Lukas MESSMANN, Sandra KÖHLER, and myself). In case the special session proposal is rejected, I am of course happy to have this talk assigned to another session.

Agricultural production entails a vast array of environmental impact. Emissions of greenhouse gases, nitrogen, or the use of ecotoxic fertilizers and pesticides put pressure on both adjacent and global ecosystems and societies. The magnitude of environmental impact caused can vary drastically between different food products or agricultural practices and a differentiation is sensible. In the current agricultural market, such environmental impacts are not internalized in food prices, which depicts externalities within the food market. The tool of True Cost Accounting (TCA) aims at monetizing such environmental impacts and internalizing it in the market prices of different foodstuff. The research on TCA yields results of "true" costs of food that can be used for different purposes. A German supermarket chain uses this true cost evaluation for informational campaigning and with it communicating environmental aspects of their food products to consumers. After conducting a face-to-face survey, and expert interviews, we draw up potentials and burdens of TCA implementation: Whilst consumers assign importance to TCA, they find financial challenges to be most burdensome for a TCA implementation; they also find policy-makers to have the most responsibility for designing policies for sustainable food markets. Experts find importance in a standardization of TCA calculation methods, as well as the design of socially just policies in order to facilitate TCA implementation. Against the background of these findings, the supermarket chain will display "true price tags" of different products in all stores across Germany for at least one week at the beginning of the second quarter in 2023. Proceedings of this campaign – profit from the added-on externalities – are donated to a German nature conservation association. Customers are be obligated to pay these externality including prices, should they decide to opt for products included in the campaign. Alleged customer behavior change is observed with changes in sales figures of products, data from member cards (Payback), customer interviews, as well as from traffic on the accompanying website. Questions we want to answer while scientifically evaluating this intervention are (i.a.): Can financial cues on environmental impact incentivize customers to consume more sustainably? What impact does the prospect of "doing good" (= donating to nature conservation) have on such alleged consumption changes? Does the overall opinion on the supermarket change for the better (because of participation in nature conservation) or worse (because of greenwashing accusations)? Results of this study can be useful for both policy makers and practitioners in achieving steps for the urgently needed agricultural transformation since it reveals insights to both effective environmental campaigning and sensible environmental economic policy.

Internalizing the environmental costs of food products: Effects on price-demand equilibria and environmental impacts

Wednesday, 5th July - 09:30: Special Session: Transition towards Sustainable Agri-Food systems: Can Financial Incentives Steer Dietary Behavior? (A1.44 KOG)

***Carlo Schmid* [1], *Lukas Messmann* [2], *Amelie Michalke* [3], *Arndt Feuerbacher* [1]**

1. University of Hohenheim, 2. Resource Lab / Center for Climate Resilience – University of Augsburg, 3. University of Greifswald

Please note: This submission is ideally part of the special session "Transition towards sustainable Agri-Food-Systems: Can financial incentives steer dietary behavior?" (proposed by Amelie MICHALKE, Sandra KÖHLER, and myself). In case the special session proposal is rejected, I am of course happy to have this talk assigned to another session.

The production of food products has significant externalities. Predominantly agricultural production, but also processing, packaging, distribution, and storage cause a vast array of different environmental impacts that threaten the climate, human health, and biodiversity alike. The costs caused by these impacts, as well as costs for damage abatement or restoration are not internalized in current market prices. This leads to a market distortion, as consumption and its costs are partially decoupled. In this work, we assess the effects of internalizing external costs into market prices on (1) equilibrium prices, (2) associated changes in demand patterns, and (3) subsequent changes in environmental impacts. In detail, we evaluate LCA-based environmental impacts of 47 different food products or product categories using the AGRIBALYSE life cycle database and the ReCiPe impact assessment method. Applying different monetization methods (e.g., Environmental Prices Handbook), we determine the external costs of these products, and conceive different scenarios for how these costs could be incorporated into or represented in retail prices by regulatory policy measures (e.g., consumption taxes and subsidies) for the case of Germany. Lastly, the costs in the different scenarios are fed into CAPRI, an economic equilibrium model for agricultural trade, markets, and demand. Intermediate results show that already small price adjustments lead to new market equilibria with more sustainable demand patterns in Germany. For instance, the current results suggest that when internalizing IPCC-based climate change costs alone, greenhouse gas emissions associated with *German consumption* would decline by 10.5 Mt CO2 eq. When also considering additional external costs from, e.g., eutrophication, toxicity, or particulate matter, this effect is amplified. However, as the CAPRI model does not restrict exports by default, the actual agricultural *supply* and the impacts associated with agricultural production are affected less strongly. hinting towards the risk of partial burden shifting. In addition, and especially in the current economic situation, there is also a limit to the extent of price adjustments that are socially acceptable and compatible – even in the policy scenarios where price increases of disproportionately harmful products are counterbalanced with subsidies for relatively more sustainable foodstuff. Despite the limitations, our study provides highly topical insights on the environmental potential of price internalization and the "polluter-pays principle", and policymakers are presented with a set of different, realistic schemes for how existing, environmentally adverse market distortions could be amended politically.

Towards True Prices in Food Retailing: The Value Added Tax as an Instrument for Agricultural Transformation

Wednesday, 5th July - 09:45: Special Session: Transition towards Sustainable Agri-Food systems: Can Financial Incentives Steer Dietary Behavior? (A1.44 KOG)

***Benjamin Oebel* [1], *Lennart Stein* [2], *Amelie Michalke* [2], *Tobias Gaugler* [1]**

***1.** Technische Hochschule Nürnberg, **2.** University of Greifswald*

Please note: This submission is ideally part of the special session “Transition towards sustainable Agri-Food-Systems: Can financial incentives steer dietary behavior?” (proposed by Amelie MICHALKE, Sandra KÖHLER, and Lukas MESSMANN). In case the special session proposal is rejected, I am of course happy to have this talk assigned to another session.

Current crises (i.e., COVID-19 pandemic, Russian invasion of Ukraine and the resulting energy and food shortages) indicate the need for robust, and sustainable supply chains with regional food production and farmland to secure food supply in the EU. Recent research shows that organic food is more resilient to supply chain disruptions and price fluctuations. In this context, we examine an approach for the sustainable and resilient transformation of agri-food networks: Can an adaptation of VAT (value added tax) levels work as financial incentives to amplify resilient agricultural practices and sustainable dietary patterns? Within the setting of the amendment of the European framework directive on the use of VAT in 2022, we model the effects of adapting the current German VAT system by (1) reducing VAT on organic vegetarian food to 0% and (2) raising VAT on conventional meat and fish to 19%. Based on historical data on organic sales shares and price elasticities, we forecast sales shares differentiated by product group for each scenario. Then, we calculate expected VAT revenues, changes in consumption patterns, and arising total external climate costs in Germany for both scenarios. Our results show that the overall consumption share of organic food would increase by 21.83% due to the modeled VAT reform compared to the status quo. Despite the VAT reduction to 0% on organic vegetarian products, the measure would yield €2.04 billion in extra VAT income in Germany per year due to the increased taxation on conventional meat products. We find that annual environmental costs of €5.31 billion can be avoided as a result of lower external climate costs of organic and vegetarian food. This will be beneficial to affected ecosystems, as well as to communities. Therefore, adjusting VAT rates in the food market would make a useful political instrument for driving organic food consumption and reducing animal livestock, which supports transitioning towards a more sustainable and resilient European food supply.

Impact Measurement and Valuation: a way for businesses to contribute to sustainable transformation?

Wednesday, 5th July - 10:00: Special Session: Transition towards Sustainable Agri-Food systems: Can Financial Incentives Steer Dietary Behavior? (A1.44 KOG)

***Zoe Elsner** [1], **Amelie Michalke** [2], **Jakob Hafele** [1], **Tobias Gaugler** [3]*

***1.** Zoe Institute for future-fit economics, **2.** University of Greifswald, **3.** Technische Hochschule Nürnberg*

Please note: This submission is ideally part of the special session “Transition towards sustainable Agri-Food-Systems: Can financial incentives steer dietary behavior?” (proposed by Amelie MICHALKE, Sandra KÖHLER, and Lukas MESSMANN). In case the special session proposal is rejected, I am of course happy to have this talk assigned to another session.

The global society faces unparalleled environmental degradation, and companies are contributing to great extent to the planets' balance disintegration. There is an urgent need for businesses to make better decisions for the people, the planet, and ultimately themselves. Currently, business decisions are largely based on financial incentives and maximising profit, which not only puts strand on the environment and societies, but ultimately can cause them losing their business cases as more sustainability action is socially and legally demanded. Further, companies and individuals will start to feel negative effects of the damage they have externalised for centuries. Therefore, a realization for better decisions-making to stay future fit is emerging.

Impact Measurement and Valuation (IMV) in its essence aims at reforming the way in which companies make decisions by measuring their impact on society and planet, and anchor this by assigning value to these measured impacts. While valuation can take many forms, recent methodologies have focussed on monetary valuations often arguing its capability of making manifold impacts comparable, and being easily understandable for managers. Several methods of impact measurement and valuation have emerged, largely carried by business consultancies leaving the field in the state of a cottage industry with many actors offering their own frameworks with little consolidation.

This paper aims to outline IMV and give an overview on which actors are operating in this space while also assessing the applicability of various IMV approaches to identify methodological weaknesses and potential for further development. This will enable an easier navigation of this space for science, media, and businesses and contribute to the streamlining of this process. Further, with this paper, the much-needed academic perspective is incorporated in the field including important ethical considerations.

We use a literature analysis to find existing IMV guides and investigate their respective methodologies. Further, structured expert interviews based on purposive sampling ensures an inclusion of all important information beyond the scope of physical reports or scripts to identify other weaknesses and potential for future development.

We found challenges, barriers, and gaps in the methodologies of IMVs. There is lack to a certain degree of data reliability primarily when measuring more qualitative impacts, like biodiversity or social aspects. There are open questions on the monetization of impacts, especially regarding ethical concerns on the morality of putting a price tag on invaluable things, like human life or healthy and natural ecosystems. We find the need of further exploring a connection between governance and IMV to put social and environmental aspects at the heart of businesses. Policies need to be established to regulate and create standards to guide companies on following IMV principles. Most voiced in interviews and papers is the need for more consolidation, since IMV currently constitute a rather confusing space of a multitude of methods. Lastly, the space lacks academic involvement, which is highly needed, especially on issues like monetization ethics.

Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities

Evaluating strategies for reducing material use in lithium-ion batteries for electric vehicles

Wednesday, 5th July - 09:00: Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities (B0.17 KOG)

Fernando Aguilar Lopez [1], ***Romain Guillaume Billy*** [1], ***Daniel B. Müller*** [2]

1. Norwegian Univ. of Science and Technology, 2. Norwegian University of Science and Technology

The exponential increase in lithium-ion battery (LIB) demand for electric vehicles (EVs) has sparked material supply concerns, which makes the understanding of the LIB system and its drivers a pertinent issue. To understand the uncertainty and sensitivity around these drivers, we introduce the MATerIaL Demand and Availability (MATILDA) model. We investigate resource use within the global LIB cycle in the context of EVs and the potential secondary material supply generated by alternative scenarios. Using this dynamic, multi-layer material flow analysis model, we conducted a detailed, time-explicit sensitivity analysis to broaden our understanding of the critical factors affecting resource supply. We identified potential problem shifts between Co, P, Ni, and Li and evaluated alternative strategies to mitigate their criticality over time. We show that social paradigm shifts such as using fewer, smaller vehicles as well as technological developments can play an important role in enabling a sustainable transition.

This abstract belongs to the proposed special session "Securing raw materials supply for electric vehicles".

Anticipating the Impacts of Global Second-Hand Electric Vehicle Trade Flows on Lower and Middle Income Countries

Wednesday, 5th July - 09:00: Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities (B0.17 KOG)

Alissa Kendall [1], ***Galym Iskakov*** [2], ***Nadiyah Helal*** [1], ***Francisco Pares Olguin*** [2], ***Margaret Slattery*** [1], ***Lewis Fulton*** [1]

1. *University of California Davis,* ***2.*** *University of California, Davis*

On-road transportation is responsible for approximately 25% of global energy-related greenhouse gas (GHG) emissions and is an enormous source of local air quality pollutants. While providing mobility options that do not rely on personal vehicles is the best way to reduce emissions, electrification of the transport sector, and in particular passenger vehicles, has been widely promoted to reduce GHG emissions and improve air quality. Lithium-ion batteries (LIBs) are the linchpin technology in advancing electric vehicles (EVs) across the world, and recent technological improvements and cost reductions have facilitated rapid increases in EV sales in China, the European Union, and the United States over last decade. While LIBs are an essential technology for an electrified future, they are also material-intensive during production and potentially hazardous at their end-of-life (EoL).

A life cycle perspective can highlight unintended consequences of vehicle electrification, namely the disproportionate burden that might be imposed by the global value chains that build EVs and which may also arise from retired EVs in the coming years. Of particular interest is the export of used vehicles from high-income countries for resale in lower- and middle-income countries (LMICs). Based on extensive review of the literature, the global second-hand vehicle trade has been absent from all previous studies focused on the life cycle environmental performance and material circularity of EVs, and has been nearly absent from the literature on the social impacts of EVs.

We use stock and flow modeling to estimate the future flows of internationally traded second-hand EVs, finding that they could exceed 2 million by 2035, up from just 30,000-75,000 in 2022. Through additional quantitative modeling of vehicle and LIB material flows at continental and national scales, as well as qualitative research on the experiences of LMICs that are early adopters of second-hand hybrids and EVs, we explore the possible implications for importing countries. Synthesis of the quantitative analysis and qualitative research is then used to make recommendations for improved governance to minimize the risk of negative impacts.

Measures to improve governance include the need to for improved export and import restrictions, such as minimum battery state-of-health or EV range conditions, access to battery information and mechanisms for ensuring the right-to-repair, and a harmonized tracking and reporting system for international used vehicle trade, among others. Historically, only importing countries have been responsible for restricting the condition of vehicles permitted to enter their borders. However, the burden of responsibility also lays with exporting nations, especially given the risk of using second-hand vehicle exports as a guise for the dumping of waste EVs and EV batteries. Export restrictions could also benefit exporting countries and regions hoping to create more circular battery material supplies by limiting the export of spent or nearly-spent batteries that are ready for recycling.

Industrial ecology methods provide a particular lens by which we can view problems and recommend solutions, with particular power to unveil potential unintended consequences. This work shows the importance of mixed-methods approaches in industrial ecology that blend quantitative and qualitative research, which are especially important when we seek to anticipate and model futures for which data are not yet available and where we risk ignoring structural inequalities and context if we rely only on quantitative models.

Using electric vehicle batteries to provide energy storage support for the electricity grid – Case study for Europe

Wednesday, 5th July - 09:00: Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities (B0.17 KOG)

***Fernando Aguilar Lopez* [1], *Dirk Lauinger* [2], *Francois Vuille* [3], *Daniel B. Müller* [4]**

***1.** Norwegian Univ. of Science and Technology, **2.** Massachusetts Institute of Technology, **3.** Etat de Vaud, **4.** Norwegian University of Science and Technology*

A wide deployment of renewable electricity generation and electric transportation requires storage for balancing the intermittent production of wind and solar energy with electricity demand and for powering electric vehicles (EVs). Within storage technologies, industry is expected to remain committed to lithium-ion batteries for the foreseeable future because of their technological maturity and rapid cost decrease. A multifunctional use of EV batteries as storage for the electricity grid, either when the batteries are still in the EVs or by reusing them after they are retired from the cars may reduce the need for additional stationary batteries. Vehicle-to-grid (V2G) can provide short-term storage when EVs sit idle, which is the case for over 90% of the time for privately owned cars. Second-life batteries (SLBs) consist of batteries whose capacity has degraded to an extent, typically between 60% and 80% of the original capacity, which does not warrant their continued use in electric vehicles, but still allows them to serve as stationary storage for the grid. The coupling of the transport and energy industries through V2G and SLBs thus holds the promise of providing more storage with fewer primary materials compared to using new batteries for grid support. In this talk, we analyze the potential of V2G and SLBs to satisfy the EU's need for stationary storage and their joint impact on primary LIB material demand. Based on a demand-constrained material flow analysis model, we find that V2G and SLBs each have the potential to exceed the demand for stationary energy storage by over a factor of two in the year 2050, which is in line with a recent global study on the storage potential of EV batteries. Combining projections by the European Commission, the International Energy Agency, and the European Network of Transmission System Operators of Electricity, we expect that EVs will need about ten times more storage than the electricity grid by 2050. Consequently, our model shows that V2G and SLBs can reduce primary LIB material needs by up to 10%. Using electric vehicle batteries to provide energy storage support for the electricity grid can thus reduce LIB material imports and ultimately make the EU less vulnerable to geopolitical tensions. Beyond the EU, these results can be of interest to other importing regions as well. Most countries will need to import LIBs or LIB materials since the LIB supply chain is even more concentrated than the supply of oil and gas.

Analysing multiple reuse and recycling in a batteries-as-a-service case

Wednesday, 5th July - 09:00: Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities (B0.17 KOG)

Maria Ljunggren [1], ***Harald Helander*** [1]
1. Chalmers University of Technology

Proposed special session:

- Title: Securing raw materials supply for electric vehicles
- Part 2: New business models and policies to reduce the raw material demand for batteries

The circular economy aims to reduce environmental impacts and resource use of production and consumption through resource-life extending strategies like reuse, remanufacturing, and recycling. Circular business models (CBMs) based on service-provisions could enable such strategies at the company level, e.g. by maintaining product and materials within company ownership throughout the product life cycle. However, the potential of CBMs to reduce resource use depends on the supply and demand of materials, components, and products over time, which is therefore important to account for when evaluating what the effects of such solutions could be.

Here, we use dynamic material flow analysis (MFA) to investigate the potential effects on raw material and product flows from implementing a CBM based on multiple reuse and recycling, until 2050. The company manufactures different types of underground mining machines and has recently started to offer lithium-ion traction batteries as-a-service to the customer. The batteries consist of standardised subpack units, which can be combined into battery packs consisting of up to seven subpacks that are sold as-a-service to the customer. The batteries are taken out of use at different levels of degradation depending on the machine they are used in, which means the subpacks can be reused across the different machines. By maintaining ownership of the batteries throughout the lifecycle, the company can manage both reuse and collection for recycling at end-of-life. To investigate how the CBM could affect the need for new batteries and raw materials under different scenarios, the dynamic MFA model traces the inflows, outflows, and stocks of the machines and their batteries over time, by cohort and reuse-stage.
Until 2050, in total 13% of new subpacks are displaced. The supply of reuse batteries is likely to eventually exceed company needs. This limits the displacement of new batteries, but at this point subpacks can be recycled or reused outside the current business model, e.g. through stationary energy storage services to be used on mining sites or by selling batteries through traditional sales. Expanding the CBM can be an important business consideration but would increase raw material demand, which can only be supplied within the CBM to a limited extent. Until 2050, the total primary material reduction is 13-59%. While reuse increases self-sufficiency of batteries, ensuring high recycling-chain efficiencies has a larger potential to reduce primary material demand than what is achieved from reusing subpacks. The effect from reuse on primary material demand is lower in a high-recycling context, but reuse becomes more important if functional recycling is limited or non-existent. For some battery metals, the proposed recycled content targets in the EU Battery Regulation are not reached in time, despite potentially high recycling-chain efficiencies.
The study illustrates how dynamic MFA can be applied at the CBM-level and contributes by pointing to opportunities, limitations, and trade-offs of reuse and recycling over longer time periods. The case is of interest due to the expected increased competition of battery materials and production capacities in coming decades, but also points to more general insights regarding the resource effects of CBMs.

How lithium-iron-phosphate batteries could affect food security and the global phosphorus cycle

Wednesday, 5th July - 09:00: Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities (B0.17 KOG)

***Fernando Aguilar Lopez* [1], *Anna Eide Lunde* [2], *Daniel B. Müller* [3]**

***1.** Norwegian Univ. of Science and Technology, **2.** PWC, **3.** Norwegian University of Science and Technology*

Anthropogenic activity is the main driving force of global warming and is re-shaping the landscape through the intensive use of resources to satisfy humanities basic needs and wants. With a growing population, the resources required to satisfy those needs, including food, shelter, and transport have been steadily increasing in the past decades. Phosphorus (P) has been an essential material in enabling the massive increase in food production through its use as a soil nutrient in fertilizers. Until recently, this had been its main application but the surge in battery electric vehicle demand has driven phosphorus use in lithium-iron-phosphate (LFP) batteries. If the exponential increase in lithium-ion battery (LIB) demand materializes as forecasted by the IEA and other studies, the transport sector could become a significant user of phosphorus through LFP chemistries. In this case, the need to decarbonize the transport sector could threaten food production by competing for the same scarce and non-renewable phosphate rock; the only precursor of elemental phosphorus. In this study, we use dynamic material flow analysis tools to investigate the effects that an increase in LFP demand could have on the global P cycle, its consequences for food security, and options to mitigate the risks by e.g. making efficient use of secondary resources.

Economics-informed material flow analysis to assess and address battery mineral criticality: a case study on copper

Wednesday, 5th July - 09:00: Special Session: Securing raw materials supply for electric vehicles Part 1: Future raw material demand for vehicle batteries – Challenges and Opportunities (B0.17 KOG)

John Ryter [1]***, Karan Bhuwalka*** [2]***, Richard Roth*** [2]***, Elsa Olivetti*** [2]

1. *United States Geological Survey,* ***2.*** *Massachusetts Institute of Technology*

The transition to a low-carbon economy dictates a transition from fuel minerals to non-fuel minerals, prompting increased concern about non-fuel mineral criticality. Criticality lies at the intersection of the impact of supply disruptions and their likelihood. Given that such disruptions reduce a mineral's availability, the primary mechanism of impact is an increase in that mineral's price. Prolonged price increases can hamper the adoption rate of low-carbon technologies. Understanding and mitigating the causes of disruption-induced price increases is therefore key to ensuring a rapid low-carbon energy transition. One approach toward achieving this goal is the augmentation of material flow analysis with dynamic feedback loops between supply chain segments, with economic relationships driving their long-term behavior. Mines, smelters, refineries, scrap dealers, and fabricators change their raw material production and consumption behavior based on the relative prices of refined metal, scrap, and intermediate ore products such as concentrate. These prices in turn are impacted by their products' production and consumption relationships, resulting in economically driven feedback loops. This work incorporates economic relationships between these supply chain components.

Previous efforts to address economic feedback have enabled more thorough investigations of potential mechanisms for industrial decarbonization, materials criticality, and the effects of international policy. Identifying and quantifying economic relationships has required highly granular time series data, requiring several years to develop and deploy the resulting supply chain models. As a result, these models have been confined to commodities with substantial data availability, such as copper or aluminum. Such data does not exist for many of the more minor minerals associated with low-carbon technologies. To bypass these data requirements, we have built a model framework that, with limited information about a given commodity, can be used to approximate the economic relationships driving each part of the supply chain. This methodology takes commodity-specific inputs such as ore grade, mine size, recycling input rates, and sectoral fractions of consumption, then fits model outputs to historical mine production, apparent consumption, and price data by tuning economic relationships using Bayesian optimization.

To date, we have completed this tuning process for aluminum, copper, gold, lead, lithium, nickel, silver, steel, tin, and zinc supply chains, reproducing historical mine production, apparent consumption, and price data with R2 goodness of fit metrics exceeding 0.6 for nearly all cases. We present these supply chain relationships. Where available, we also compare historical and modeled mine costs, refining charges, and ore grades. While this method is applicable to several key battery minerals, we present the copper results as a validation commodity due to its copious data availability. We demonstrate the capabilities of this approach in determining the likelihood of price excursions and supply shortfalls with and without supply chain disruptions. Finally, we identify the importance of economic relationships and characteristics of mining, refining, manufacturing, and recycling supply chain components that drive price excursions and supply shortfalls, and suggest mechanisms for mitigating these effects.

Part of the special session: SECURING RAW MATERIALS SUPPLY FOR ELECTRIC VEHICLES

LCA methods 2

Towards a multifunctional version of the ecoinvent 3.9.1 database

Wednesday, 5th July - 09:00: LCA methods 2 (C0.06 KOG)

Jeroen Guinée [1]***, Reinout Heijungs*** [1]***, Guillaume Bourgault*** [2]
1. *Leiden University,* ***2.*** *ecoinvent*

The ecoinvent database has been published as several system models: namely, “Allocation, cut-off by classification”, “Allocation, cut-off, EN15804”, “Allocation at the point of substitution” and “Substitution, consequential, long-term”. System models consist of an allocation step (turning all multifunctional processes into monofunctional ones) and a linking step (linking unit processes to upstream and downstream unit processes). However, the basis of all system models is the same pool of individual processes of human activities called “Undefined Unit Processes (UPR)”. Each system model applies different assumptions to determine the supply (linking) and the distribution of impacts between producers and consumers of products and services (allocation and substitution). Particularly the allocation and substitution step is a methodological step that is recognized as potentially influential for the results of a specific LCA study. Since different choices to solving multifunctionality are possible, this methodological step should preferably be left to the practitioner and not be part of a *data*base. A unique feature of CMLCA software is that it supports different solutions to multifunctional processes. Therefore, as a joint effort between ecoinvent and Leiden University, we aim at importing the UPR data in CMLCA software and eventually performing Monte Carlo simulations jointly with CMLCA software to propagate the uncertainty related to the choice of partitioning methods for allocation for all relevant multifunctional processes present in the ecoinvent 3.9.1 database simultaneously. At the conference we will present the preliminary results of this currently ongoing exercise.

Substitution coproduction modeling is actually compatible with attributional life-cycle assessment

Wednesday, 5th July - 09:15: LCA methods 2 (C0.06 KOG)

Arianne Provost-Savard [1], ***Guillaume Majeau-Bettez*** [1]

1. *CIRAIG, Polytechnique Montréal*

A vast majority of life-cycle assessment (LCA) studies use the attributional perspective. This approach aims to attribute a state-descriptive footprint (or share of global anthropogenic environmental impacts) to a normatively circumscribed system providing one or multiple functions. The attributional approach essentially asks an accounting question, striving to associate footprints with consumptions, such that all final consumption (product that is directly consumed by humans and not used in other products' life cycles) footprints add up to the sum of anthropogenic environmental impacts (additivity characteristic). Multifunctional systems (i.e., providing two or more functions simultaneously) comprising processes that are not technologically subdivisible between co-functions, are frequently encountered in LCA studies. In this case, we have to resort to coproduction modeling techniques, and the *ISO 14044* standard recommends to prioritize the system expansion approach. The classical definition of system expansion refers to the enlargement of the functional unit to integrate the value chains of the multiple products involved in the coproduction issue. The substitution approach, consisting in assigning all impacts of the system to the main function, minus the impacts avoided through the substitution of primary productions by its secondary production(s), is also widely used in the LCA literature as a system expansion approach. The classical system expansion and the substitution approaches are considered to yield commensurate results, and used as equivalent methods. However, a dissenting body of literature argues that while the classical system expansion approach is perfectly compatible with all the methodological characteristics of attributional life-cycle assessment (ALCA), the substitution approach does not allow for a conservation of global environmental impacts, and interferes with the state-descriptive characteristic of attributional studies. There is thus a major contradiction in guidance on the use of substitution in ALCA: system expansion and substitution cannot both be methodologically equivalent and, at the same time, differ as to their fundamental compatibility with ALCA. The main objective of this research is to shed light on common misconceptions about the agreement of substitution with the fundamental characteristics of ALCA. The first misconception is that *the use of substitution in ALCA violates the conservation of environmental impacts*. We explore the origin of this widespread misconception, to find out it arises from an incomplete and erroneous methodology used to attribute impacts to the secondary product(s) with the substitution approach. We show with a generalization framework that these impacts must correspond to those of the substituted primary production(s); otherwise, imbalances may occur and lead to a violation of the additivity characteristic. The second misconception is that *because ALCA describes a system in a given state, and substitution describes a change in state (a perturbation, something avoided), the two cannot logically and coherently be mixed.* Our reflections and the illustration of the problem with a generalization framework led us to conclude that it is possible to describe an attributional state-descriptive system in terms of a past or inferred (substitution) change, rather than as disrupted by a change. The use of substitution modeling can therefore confer an economic causality meaning to the distribution of environmental impacts between the main and secondary productions, without disrupting the state-descriptive characteristic of attributional studies. In light of the reflections made, we recommend to authorize substitution modeling in ALCA studies. This study is a step forward in clarifying the methodologies that are suitable for coproduction modeling in ALCA.

Solving multifunctionality in LCAs of circular systems: the case of building-integrated agriculture

Wednesday, 5th July - 09:30: LCA methods 2 (C0.06 KOG)

Joan Muñoz-Liesa [1]***, Jeroen Guinée*** [2]***, Anna Petit Boix*** [1]***, Xavier Gabarrell i Durany*** [1]***, Eva Cuerva*** [3]***, Santiago Gassó-Domingo*** [3]

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Circular economy practices are gaining increased maturity levels in all sectors of society. By minimizing waste and optimizing the use of resources through closed-loop systems, multiple functions can often be derived from a specific product system. This poses a problem to life cycle assessment (LCA) partitioners, who need to deal with multiple functions among the product system under assessment. The challenge is thus to allocate environmental impacts to each function produced within the product system. In this work we aim to provide an example of handling the multifunctionality problem in LCA in a circular system. In particular, here we analyzed a case study of the ICTA-UAB building (Barcelona), a circular building which incorporates a rooftop greenhouse able to produce vegetables all-year around while also improving the building bioclimatic strategy. Like other urban agricultural forms, building-integrated agriculture (BIA) is in general a circular system serving multiple functions values *per se* since it aims to exploit synergies between greenhouses and buildings. Based on previous assessments, we discussed the co-products/-functions derived from this system and how different methodological criteria for dealing with this multifunctional situation in an LCA influence environmental results. This is important since the greenhouse is fully integrated with the building, and thus, allocating resource inputs and outputs for each function is not straightforward. For instance, considering the waste heat from the building as a waste or as good to the rooftop greenhouse significantly influence allocation rules and the derived environmental impacts. Although here we test multiple ways to solve this multifunctional problem, a possible solution to allocate resources is to virtually divide the systems in two virutal systems according to the economic value of both co-products. By doing so, we identified that the combined tomato production together with the energy-saving effect from the greenhouse represents an environmental benefit compared to other existing mono-functional systems. Overall, we aim to provide new insights on how to design and deal with circular systems from an environmental perspective to make informed decisions about product and service design in circular systems.

Quantifying spatially and temporally explicit life cycle impacts of Midwestern US corn - cover crop - soybean systems to inform cover crop marketization initiatives

Wednesday, 5th July - 09:45: LCA methods 2 (C0.06 KOG)

Kathryn Phillips [1], ***Timothy Smith*** [1]

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The transition to sustainable agriculture will rely not only on developing sustainable management practices, but also on creating policies and market mechanisms to support their implementation. In the midwestern United States, marketization of cover crops has emerged as a promising approach to incentivize farmers to plant winter cover crops in corn-soybean rotations, which could increase soil carbon sequestration and decrease nitrogen leaching. However, complex interactions between cover crops and on-field nitrogen and carbon dynamics cause variable benefits and drawbacks (such as yield decreases) across different locations. This variability, as well as the potential impact of climate change on the benefits of marketized cover crops, have not yet been thoroughly explored.

We use spatially and temporally explicit modeled corn, soybean, and cover crop data and a life cycle assessment framework to answer: How will the global warming and eutrophication impacts of corn and soybeans change with the addition of a winter cover crop? How will this be affected by climate change? How will the impacts change if the cover crop is marketed as its own product?

Using the biogeochemical model *ecosys* and estimates of upstream impacts from GREET, we create spatially and temporally explicit life cycle inventories at a fine granular scale of key impacts of corn-soybean rotations under present and future weather conditions with and without a winter rye cover crop. The life cycle inventories for each of these scenarios serves as the basis of a cradle-to-farm-gate life cycle assessment of the whole rotation and of each crop. Furthermore, we explore how allocation methods affect the outcome of the assessments. Comparing the results of these LCAs allows us to explore how cover crops may influence the environmental impact of corn-soybean systems now and in the future, and how marketization of cover crops may alter impacts. These results are important for those who wish to promote cover crop planting through marketization of cover crop products, and for those who wish to market cover crop products by promoting their environmental benefits.

Spatiotemporal analysis on the future carbon footprint of renewable energy by a dynamic life-cycle assessment: a case study on solar electricity in the United States

Wednesday, 5th July - 10:00: LCA methods 2 (C0.06 KOG)

Jiaqi Lu [1], ***Jing Tang*** [1], ***Rui Shan*** [2], ***Guanghui Li*** [1], ***Pinhua Rao*** [1], ***Nan Zhang*** [3]

1. *Shanghai University of Engineering Science,* ***2.*** *University of North Carolina at Chapel Hill,* ***3.*** *The University of Manchester*

To mitigate the threat of global climate change, anthropogenic greenhouse gas (GHG) emissions should be reduced to net zero by 2050. The fossil fuel combustion associated with energy consumption is the main source of GHG emissions; thus, the decarbonization of the energy sector is an urgent issue. The rapid expansion of renewable energy is a vital pathway, where solar photovoltaic (PV) will be the most significant contributor to the GHG emission reduction. The global installed capacities of solar electricity are expected to increase by 20 times to achieve carbon neutrality. Solar PV is zero-emission during the operation; while, from a life-cycle perspective, considerable greenhouse gas (GHG) emissions are generated during the manufacture of PV panels. At present, the electricity consumption accounts for approx. 75% of GHG emissions in the cradle-to-gate process of PV panel production. Thus, the future carbon footprint of renewable energy facilities will also decline with spatiotemporal variances depending on the decarbonization progress of the energy sector. The interaction between the grid decarbonization and carbon footprints of solar PV would be critical for planning the panel manufacturing to fully realize its environmental benefits. Herein, a dynamic life-cycle assessment (LCA) model is developed to elucidate the cumulation of installed PV panels with heterogenous carbon footprint if manufactured and installed in the U.S. First, the accumulative electricity consumption of cradle-to-gate PV panel production and the corresponding GHG emissions were refined from ecoinvent database. The potential change in the electricity production mix for each state in the U.S. was referred to Standard Scenario Report (mid-case scenario) modeled by National Renewable Energy Laboratory. Based on our proposed dynamic model, the state-level carbon footprint of solar electricity ($CFE_{\text{PV-avg}}$) from 2022 to 2050 was estimated by several production scenarios for accounting the GHG emissions from the cradle-to-gate production of PV panels. Considering the decarbonization of the national power grid, the $CFE_{\text{PV-avg}}$ (min 0.032, max 0.051, weighted avg. 0.040 kg CO_2-eq/kWh) in 2050 will be significantly lower than the benchmark (min 0.047, max 0.068, weighted avg. 0.056 kg CO_2-eq/kWh) which does not consider the dynamic change of embodied carbon in the PV panels. We also found that the elimination progress of thermal plants has a significant influence on the carbon footprint of solar electricity and electricity mix. The proposed dynamic LCA framework considering the heterogeneous embodied carbon is promising to support the design of solar PV supply chains and, ultimately, the supply chain for the whole carbon-neutral energy system.

Quantifying Collision and Electrocution Impacts of the Electric Grid on Biodiversity

Wednesday, 5th July - 10:15: LCA methods 2 (C0.06 KOG)

Dafna Gilad [1]***, Roel May*** [2]***, Bård G. Stokke*** [2]***, Francesca Verones*** [1]
1. NTNU, 2. NINA

A key to mitigating climate change is the reduction of our dependence on fossil fuels by transitioning to cleaner, renewable energy sources. However, the foundation of a sustainable energy system is its electricity grid. Today, about 80 million kilometers of power lines cross countries and continents worldwide to provide us with electricity. The current electricity network must inevitably expand within the next decades: new transmission lines will link new renewable power plants to the local grid, while additional distribution lines will ensure the delivery of stable and reliable electricity to consumers. Yet power lines act as a physical barrier for bird species: around the globe, hundreds of millions of birds are killed annually by power lines due to collision and electrocution. Life cycle assessment (LCA) is a suitable framework to provide a holistic view of the environmental impacts of energy systems. Indeed, life cycle impact assessment (LCIA) models were recently developed to evaluate the impacts of hydropower and wind power on biodiversity. However, these models assess only the effects of electricity production, overlooking the impacts of electricity transmission. Furthermore, current LCA studies on power lines focus on certain impact categories, neglecting the potential damage to ecosystem quality. We present the first LCIA models to quantify the impacts of electricity transmission on birds. Our models produce maps of the potentially disappeared fraction of species (PDF), which predict the risks of collision and electrocution on a large scale. These maps show how these impacts vary spatially, identify susceptible bird species, and indicate how efficient electricity transmission is across different areas. To validate the methodology, we applied them to the energy system of Norway. The majority of Norway's energy system is based on electricity from renewable sources, and the country leads a low-emission energy policy that aims to reduce its emission by half before 2030. Overall, the characterisation factors ranged between 3.9 x 10-15 and 8.4 x 10-16 (PDF*yr/kWh) for collision and 1.9 x 10-16 and 6.5 x 10-16 (PDF*yr/kWh) for electrocution. Gallinaceous birds, waterfowl, and waterbirds were the most susceptible to colliding with power lines, and electrocution posed a greater threat to raptors, owls, and corvids. Transmission lines had higher collision impacts in densely populated areas in southern Norway, while the electrocution effects of distribution lines were greater in northern Norway. Our models are not limited to Norway. By obtaining appropriate input data, they can be applied to any region. The integration of these models in LCA is essential, not only because they introduce two new impact pathways but because they take us a step further in assessing the impacts of energy systems in a holistic way: addressing both the effects of the production and transmission of our electricity on biodiversity.

EEIOA methods

A Framework for Adding Novel Satellite Accounts to the EXIOBASE3 MRIO System

Wednesday, 5th July - 09:00: EEIOA methods (B0.25 KOG)

Konstantin Stadler [1]***, Candy Deck*** [1]***, Richard Wood*** [1]

1. *NTNU*

EXIOBASE is a widely used Economic-Environmental Input-Output (EE-MRIO) database, but it has limited flexibility for adding additional stressors or satellite accounts on the fly. While the Open Source MRIO analysis package Pymrio does offer some ability to exchange and extend satellite accounts, it does not have any infrastructure behind it for sharing these data in a consistent way. Nevertheless, several groups have compiled additional satellite accounts for EXIOBASE. While most of these are Open Data, they are cumbersome to find and use.

Here we present a new framework for adding novel satellite accounts to the EXIOBASE3 MRIO system. The framework consists of three components: (i) an automatically generated project template based on the Python Cookiecutter system, (ii) an Open Source toolbox for handling common satellite account modification tasks, (iii) an Open Data repository (based on a Zenodo community) for sharing the new satellite accounts. To support the reuse of this new data, Pymrio will have new functionality to automatically gather the new satellite accounts from the repository and combine it with the EXIOBASE MRIO.

In the presentation, we include a tutorial in which we will go through the whole workflow with some novel satellite account dataset, starting from getting new extension data, data cleaning and modifying to fit it to EXIOBASE, and finally doing some footprint analysis with the novel extension.

We will also discuss potential developments, particularly how the system could be extended to other EE-MRIO systems.

With this framework we aim to promote transparency, reproducibility, reuse, and collaboration in the MRIO community with a first focus on satellite accounts.

The Legacy Environmental Footprints of Capital Stocks

Wednesday, 5th July - 09:15: EEIOA methods (B0.25 KOG)

Ranran Wang [1]***, Edgar Hertwich*** [2]***, Tomer Fishman*** [3]***, Sebastiaan Deetman*** [4]***, Paul Behrens*** [5]***, Wei-Qiang Chen*** [6]***, Arjan de Koning*** [1]***, Ming Xu*** [7]***, Kira Matus*** [8]***, Julie Zimmerman*** [9]

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The foundations of today's societies are provided by the historic accumulation of capital assets driven by investment decisions through time. Green finance seeks to achieve sustainability by investing in different assets. However, the predominant focus of science and policy has been on the environmental impacts of the day-to-day running of assets. We integrate 50 years of economic and environmental data to provide the global legacy environmental footprint (LEF) of investments and unveil the materials extractions, greenhouse gas (GHG) emissions, and health impacts accrued in today's capital stock. We analyze LEF trends and map LEF to the current production and consumption system to identify hotspots and mitigation levers, which enable investigations of future LEF trajectories. We show that from 1995 to 2019 global LEF more than tripled in most material extractions, GHG emissions, and health impacts, which outpaced GDP and population growth in the same period. In contrast to popular messages that the environmental footprints between developed and less-developed economies have converged in recent years, the LEF shows a larger or growing gap. We find that capital accumulation to 2050 could add a further 185-583 GtCO_2eq (42-132% of the carbon budget for 1.5°) and triple the impacts in other environmental factors. The LEF offers an important framework for assessing investment decisions and mitigating sustainability threats and inequalities resulting from accumulating capital.

The trouble with energy accounts: a step towards a standardised procedure

Wednesday, 5th July - 09:30: EEIOA methods (B0.25 KOG)

Kajwan Rasul [1]***, Richard Wood*** [1]***, Sarah Schmidt*** [2]***, Edgar Hertwich*** [1]

1. *Norwegian Univ. of Science and Technology,* ***2.*** *Norwegian Univ. of Science and Technology & SINTEF*

Constructing, globally consistent, energy and energy-related emissions accounts for multi-regional input-output (MRIO) models are particularly challenging. Unlike most other satellite accounts in IO modelling, energy products are used (degraded) by almost all sectors in the economy and a simple direct allocation to energy sectors is therefore insufficient. Furthermore, energy accounts often must be transformed from the territorial accounting principle to residential accounting principle. MRIO developers approach these challenges in different, and often non-transparent, ways, which give rise to significant discrepancies in the accounts, and thereby calculated footprints.

There is a strong need for harmonised energy accounts that are commonly accepted by the scientific community. To achieve such, we believe that transparency and collaboration through open sourcing is necessary. Open sourcing the procedure code will allow the rest of the input-output community to dissect and contribute to the development of these extensions. Furthermore, a standardised procedure will allow MRIO developers to apply the same procedure to their MRIOs with minimal efforts.

In our work, we present a new procedure for creating energy and associated emissions extensions for EXIOBASE using the *World Energy Balances* (WEB) provided by the International Energy Agency. The procedure builds on the previous version but provides significant improvements in terms of (1) stability, (2) timeliness, (3) transparency, and (4) higher country resolution.

When benchmarking the new and old EXIOBASE emission accounts with EUROSTAT's official production-based accounts, we see a reduction in root-mean-square deviation from 2.16 to 1.93 tons CO2 equivalent per capita. The number of extreme outliers in both the energy and emission stressors are also significantly reduced due improved consistency between monetary and physical flows.

In our presentation, the main steps of the developed procedure will be presented before the audience is invited for a discussion on the modelling choices made. Furthermore, we would like to discuss how the broader community (IO modellers and industry specific experts) may contribute to creating such standardised procedures. This may serve as a first, in a hopefully long list of collaborations, on standardising procedures for MRIO environmental accounts.

A Dynamic Agent-based Environmentally Extended Input-Output Model and Its Application to Firm-level Environmental Risks

Wednesday, 5th July - 09:45: EEIOA methods (B0.25 KOG)

Shen Qu [1]

1. *Beijing Institute of Technology*

The Environmentally Extended Multiregional Input-Output Model (EE-MRIO) is a crucial tool in industrial ecology. However, previous models have been limited to either static models or dynamic models with a time step of at least one year, lacking the ability to utilize data with finer temporal resolution and failing to accurately model supply-side environmental risks. With advancements in “big data” and GPU computing power for matrices, we introduce the Climate-resilient and Low-carbon Unfolding Economic Scenarios (CLUES) model, a dynamic agent-based model that can simulate the evolution of an input-output system, whether monetary or physical, single or multi-regional. The model can unfold scenarios at relatively fine temporal scales, such as days, and can be applied to any input-output system with multiple producers, consumers, and transporters, given enough data and computing power.

Furthermore, we present an application of the CLUES model in managing firm-level environmental risks. By exploring how local environmental policies alter environmental risks and economic states in multiple regions, we analyze the economic and environmental consequences of a policy regulating chemical enterprises in Jiangsu, China. Our model, which couples a dynamic agent-based supply chain model with firm-level information, shows an indirect loss of over 80% in overall economic cost due to supply chain propagation when ~1,800 chemical enterprises shut down under the policy from 2019 to 2021. The results of our counterfactual analysis indicate that the timing and duration of the shutdown and rectification of the chemical enterprises are more significant factors in the supply-chain losses than the duration. Multi-objective policy optimization considering environmental, safety, and economic standards is feasible for reducing risks in all three areas. Our real-time simulations provide valuable information for policy designers to formulate environmentally and economically friendly policies and alert stakeholders to the losses of the supply chain network in advance. The developed model can also be extended to optimize economic and environmental sustainability caused by other environmental risks, natural disasters, and policy scenarios.

Bridging the resolution gap - Linking MRIO environmental indicators to the HS6-level using economic complexity methods

Wednesday, 5th July - 10:00: EEIOA methods (B0.25 KOG)

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Industrial Ecology faces challenges in bridging the gap between top-down (input-output based) and bottom-up (process-based) analysis, especially when it comes to environmental impact assessment. Top-down Multiregional Input-Output (MRIO) Databases have a limited (although increasing) resolution, making it difficult to connect environmental indicators to specific products. World trade data (e.g. UN Comtrade or BACI; Gaulier & Zignago, 2010), on the other hand, provides a global, standardised overview of countries' imports and exports at much higher resolution, but lacks a connection to environmental pressures.

While trade data has been used extensively in industrial ecology to study flows between regions, using countries' export data as a proxy for their domestic production has seen little application. This practice is standard in the field of economic complexity (Hidalgo, 2021), where this methodology is used to quantify the skills and capabilities required to produce products (product complexity) and those present in economies (economic complexity).

In this research, we adapt methods from economic complexity research to link sectoral environmental indicators from EXIOBASE 3 (Stadler et al., 2019) to BACI data at the HS6 product category level. This provides an estimation of the overall environmental impacts of production of HS product categories in the time period 2000-2016. We subsequently focus on the results for greenhouse gas emission indicators, comparing these to other HS-level estimates and analysing the relationship between product complexity and greenhouse gas emissions. Lastly, we investigate whether "green product" categories (i.e. product categories classified as having environmental benefits by WTO, APEC or OECD; Mealy & Teytelboym, 2020) on average are associated with lower greenhouse gas emissions than other product categories.

This research shows the effectiveness of this methodology to increase the resolution of environmental indicators. This increased resolution enables a fine-grained understanding of product environmental impacts, makes it easier to link such impacts to trade, and allows policymakers to identify high-impact products and disincentivise their production. Furthermore, this work provides a first insight into how techniques from the field of economic complexity can be applied in industrial ecology, opening the door for future such applications.

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IE and business

The roles of Regenerative businesses in Industrial and Urban Symbiosis development

Wednesday, 5th July - 09:00: IE and business (B0.31 KOG)

Kristina Nyström [1], ***Murat Mirata*** [1]

1. Linköping University

Industrial and Urban Symbiosis (IUS) refers to inter-organisational solutions enabling more resource-efficient industrial and urban systems by valorising underutilised resources. However, realisation of IUS solutions meets several barriers (e.g. Henriques et al., 2021; Rodin et al., 2021). A profound barrier is that involved companies often regard realisation of IUS as a side activity, with lower priority than core business (Posch et al., 2011). An overlooked topic in research is the role of private companies that in different ways promote IUS as their core commercial activity (Velenturf 2017), which we label as "regenerative businesses" (RBs). Such knowledge is important as it can inform policy measures intended to accelerate the transition towards more circular economies. To fill this knowledge gap we are studying the impacts of RBs in realisation of IUS solutions, using a longitudinal multiple case-study design (Yin, 2018). Impacts are studied by identifying change-processes RBs initiate and drive, and the resulting outcomes in the light of contextual factors (Pettigrew 1997). Five cases focusing on different IUS solutions with large potential to scale up in other contexts have been followed for 3 years, complemented by retrospective investigations. The cases include valorisation of low-grade waste heat, construction waste, nutrients in effluents, waste sand, and salts in ashes. Regular interviews are performed with several informants per company. To enhance validity of detected impacts, other involved actors are interviewed and documents are studied. In the analysis of impacts, processes and outcomes are mapped on different analytical levels, using definitions provided by Spekkink et al. (2013). A cross-case analysis is done by comparing the cases to each other.

Based on the results we will make three major contributions to the IUS literature. First we empirically show the importance of a new type of actor that has IUS realisation as part of their core business, in line with predictions by for example Chertow & Park (2016) and Aid et al (2017). Results show RBs' pivotal, and differing, roles in realising IUS solutions. These include: a) finding or creating innovative ways to valorise wastes into marketable products; b) orchestrating IUS networks around different anchor tenants, and; c) enabling measures by other actors.

Second, we reveal that action from public actors are important to empower RBs in different ways, and that the roles of public and private actors in certain stages of realisation can be even more integrated than has been argued for example by Uusikartano et al. (2022). Third, we open up for research on RBs' impact on structural mechanisms of IUS development by suggesting that RBs not only realise certain IUS solutions, but also collectively can create more fertile conditions for further IUS development. While this to some extents has been captured by research on regional intuitional capacity (Spekkink, 2013) we also add observations of increased internal capacity as well as impacts on a wider societal level. Together these findings contribute to increased understanding of facilitated IUS as an interplay between public and private actors outlined by Costa & Ferrão (2010).

Guidance for further research include further investigations of: conditions, including public policy, that enable RBs emergence and impacts; persistent challenges of RBs and their links to structural barriers to IUS, and; RBs' business models.

Challenges for military decarbonization: how Industrial Ecology can help

Wednesday, 5th July - 09:15: IE and business (B0.31 KOG)

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Among different sectors contributing to greenhouse gas (GHG) emissions, the military sector is responsible for consuming huge amounts of fossil fuels and generating a great deal of GHG emissions (Parkinson and Cottrell, 2021). Obviously, their main aim is to provide “national security” but as the global military expenditure of $2.08 trillion will rise significantly, so will their GHG emissions (Belcher et al., 2020). This presentation describes the major challenges in decarbonizing militaries and provides some suggestions from the Industrial Ecology community on how to help the sector to act upon (Rajaeifar et al., 2022).

As a first step in combating climate change, actions on mitigation are only effective if they unambiguously and correctly measure, reports, and reduce GHG emissions. The estimations show that the world’s militaries emissions could stand somewhere between 0.4 to more than 2 billion metric tonnes of CO_2eq annually (Lin and Burton, 2020). Yet, the militaries have been largely exempted from reporting their emissions, despite the huge collective consumption of fossil fuels by the sector (Crawford, 2019). Military GHG emission measurement and reporting is not a requirement of, or part of international climate change agreements such as the 2016 Paris Agreement. This makes targets to cut military emissions akin to guesswork, and thus less effective.

The main issue in assessing the impact of military activities is that robust and comprehensive data on military emissions is not publicly available. Moreover, there is a lack of consistent methodology for tracking emissions on military bases or in conflict areas (Rajaeifar et al., 2022). It is essential that the international community of researchers, policy makers, and governments address the gap and provide standardised assessment methodology and create a comprehensive assessment framework for military GHG emissions, including life-cycle embedded emissions. Here, some Industrial Ecology (IE) means such as material flow analysis (MFA) and life cycle assessment (LCA) could help effectively. Moreover, considering emissions associated with warfighting activities is vital for understanding the climatic consequences of armed conflicts.

Another big challenge is that militaries have locked themselves into various fossil fuel-dependent operations and equipment for the next few decades owing to long procurement processes and lifespans (Rajaeifar et al., 2022). The military mitigation programs must prioritise energy efficiency improvements and fuel-switching programs for military bases as well as military equipment such as warships, combat aircraft, and ground vehicles. Each of these solutions should be validated using different IE means.

The greater use of renewable energy such as solar photovoltaic arrays as well as electric vehicles should become a norm at military bases (Rajaeifar et al., 2022), while greater use of hydrogen and other emerging technologies should be considered for long-term. The emerging technologies need to be carefully studied from the viewpoint of their life cycle environmental impacts and raw material requirements using prospective LCA and MFA to consider any unintended consequences of the technologies in the future (Baars et al., 2022; Bergerson et al., 2020). These are also national security concerns to be considered when transiting toward emerging technologies in a world in turmoil. Furthermore, there is an opportunity to benefit from some other IE means such as Industrial Symbiosis and Urban Metabolism to provide effective solutions for decarbonizing militaries.

Climate Innovation: From carbon accounting to business integration

Wednesday, 5th July - 09:30: IE and business (B0.31 KOG)

Dara O'Rourke [1]

1. University of California, Berkeley

There has been rapid growth in the number of corporations announcing net zero carbon goals over the last three years. However, there remains a significant gap between current corporate actions and actually achieving net zero carbon by 2050. Current methodologies to evaluate firm performance on decarbonization are immature, based largely on proxy measures (such as reporting annual total emissions and long-term goals), that remain highly contentious. This paper analyzes – through both quantitative and qualitative data on greenhouse gas emissions, corporate abatement initiatives, and innovation processes - a small group of firms that are implementing actions to achieve net zero carbon. We evaluate these actions through the lens of corporate innovation theory, identifying five foundational steps to climate innovation: 1) carbon accounting and public reporting; 2) detailed internal measurement and instrumentation; 3) carbon intensity reductions through efficiency actions; 4) absolute carbon reductions through adoption of low-carbon technologies; and, 5) long-term innovation processes to transform "hard-to-abate" sources of emissions. We conclude with improvements to evaluative criteria, and lessons for both corporate leaders and IE practitioners working to motivate firms to move faster to implement processes to drive decarbonization. The research holds significant implications for the IE community and its role in producing actionable metrics that businesses can more effectively integrate into innovation processes to decarbonize products and supply chains.

Modernizing cement manufacturing in China leads to significant environmental gains

Wednesday, 5th July - 09:45: IE and business (B0.31 KOG)

beijia huang [1]

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In recent decades, China has witnessed a construction boom and, thus, an enormous amount of cement use, while its cement manufacturing technology (CMT) has experienced rapid upgrading. Understanding such combined effects on environmental burdens is important for exploring environmental mitigation strategies for cement manufacturing. Here, we present the CMT evolution based on the national- and provincial-level data by adopting regression models. We show that southern and eastern China are leading CMT upgrading and construction activities. Also, a comprehensive assessment of the environmental impact of CMT renewal in China is conducted by applying a life cycle assessment and scenario analysis. Climate change, fossil depletion, and photochemical ozone formation are identified as the key environmental burdens of cement manufacturing. While particulate matter formation appears to be the most prominent beneficiary of CMT upgrading. Until 2021, CMT upgrading led to a 25%~53% reduction in the environmental burden of cement manufacturing by environmental impact category. Besides, we find the CO_2 emissions and electricity use per ton of cement production in China are lower than in most other developed countries. Our results can help inform both global and national planning on credible pathways towards a sustainable and environmentally friendly cement industry.

The environmental costs of consumer product returns

Wednesday, 5th July - 10:00: IE and business (B0.31 KOG)

Tamar Makov [1], ***Rotem Rotem*** [1], ***Benjamin Sprecher*** [2], ***Shira Shabtai*** [1], ***Vered Blass*** [3]

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During the 2020 holiday season alone, US consumers sent more than one million products back to retailors each day(!). Consumer returns are a particularly challenging issue in e-commerce where as many as 20%-40% of all products sold are returned. While many consumers consider return policies to be a key factor in their purchase decisions, few seem realize that the products they send back don't necessarily make it back to the shelf. Instead, many returns travel through a complex reverse logistics supply chain, at the end of which some are resold via outlets and secondary markets at a fraction of their original retail price, while others are recycled, donated, or sent directly to incineration.

Beyond the added transport and waste associated with the post-return lifecycle stages, disposing of brand-new perfectly functional products also squanders the embodied materials and energy invested in their production and distribution. While the environmental impacts of eCommerce are well discussed, returns are seldom included in analyses. As a record number of households adopt eCommerce following the global pandemic, gaining a better understanding of the environmental implications of such a massive shift in consumption patterns is both timely and imperative.

Building on a unique dataset covering over 600,000 apparel items returned in the EU, semi-structed interviews with industry experts, and a comprehensive literature review, we use data-science methods and LCA, to map the flows of returned items across the post-return supply chain and assess the full lifecycle environmental impacts of product returns. Our results suggest that the embodied impacts associated with producing items that are never used far surpass the direct emissions associated with transport, processing and packaging of returned products. To the best of our knowledge, this work presents the first attempt to quantify the environmental impacts of product returns from a full lifecycle perspective

Building & Infrastructure 3

Embodied greenhouse gas reductions in single-family dwellings: Drivers of greenhouse gas emissions and variability between Toronto, Perth, and Luzon

Wednesday, 5th July - 09:00: Building & Infrastructure 3 (B0.13 KOG)

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Reducing embodied greenhouse gas (GHG) emissions in the construction of buildings is increasingly recognized as necessary to meet medium- and long-term climate targets. To date, the focus of efforts to reduce embodied GHG have been on using lower GHG intensity materials through material switching (e.g., wood vs concrete buildings) or changing the manufacturing of materials to reduce their GHG intensity (e.g., blast oxygen furnace to electric arc furnace in steel manufacturing). Much less attention has been paid to the potential to reduce embodied GHG by reducing how much material is used for construction of buildings. The central contribution of this work is that we examine the relative importance of material intensity (MI) and material GHG intensity to overall embodied GHG emission intensity of buildings, with specific focus on single-family dwellings (SFDs). Three design and material pathways (light-weight design of structures, more intensive use through less floor area, very low GHG materials) were evaluated for their potential to decarbonize housing construction.

We estimate the cradle-to-gate embodied GHG emission intensity of SFDs in Toronto, Canada, Perth, Australia, and Luzon, Philippines using two estimation methods, most likely embodied GHG emission intensity and a probabilistic estimation model employing Monte Carlo simulation. Material intensity data for 40 wood-concrete SFDs in Toronto, 20 brick-concrete SFDs in Perth, and 20 reinforced concrete SFDs in Luzon form the foundational data of the analysis (Arceo et al., 2023). Material GHG intensity is used to convert MI to building embodied GHG emission intensity of SFDs and collected from Environmental Product Declaration reports, Quartz database (Quartz, 2022), EPiC database (Crawford et al., 2019), and life cycle assessment publications.

In the probabilistic model, we characterize input distributions from the MI and material GHG intensity data and propagate them to estimate the embodied GHG emission intensity of 10,000 SFDs in each of the case study location. Principal component regression for embodied GHG emission intensity across 10,000 SFDs for each location is used to determine which between the observed ranges of MI and material GHG intensity are driving embodied GHG emission intensity of SFDs. Finally, we estimate potential reductions in the embodied GHG intensity of the modelled SFDs using three mitigation scenarios drawn from literature.

The most likely embodied GHG emission intensities of the SFDs vary across locations with differences driven by construction norms (e.g., construction type, living space conditions) and materials manufacturing (affecting material GHG factors). Accordingly, Toronto SFDs have embodied GHG emission intensities of 158 kg CO_2 eq/m^2 (*SD*=28), Perth SFDs have 145 kg CO_2 eq/m^2 (*SD*=24), and Luzon SFDs have 310 kg CO_2 eq/m^2 (*SD*=64). On a per building functional unit, Toronto SFDs have 71,300 kg CO_2 eq/m^2 (*SD*=23,700), Perth SFDs have 38,200 kg CO_2 eq/m^2 (*SD*=9,700), and Luzon SFDs have 82,000 kg CO_2 eq/m^2 (*SD*=64,600). The variation in embodied GHG intensity within the studied cases is dominated by material quantities (contribution to variance of 71%-94%) with less influence from embodied GHG factors, albeit the wide range of materials material GHG intensity. Cascading strategies starting from readily deployable strategies (light-weigh design of structures, more intensive use) followed by strategies that require long-term technology and infrastructure changes (very low GHG materials) are shown to have the potential to reduce embodied emissions in half (47% to 51%) and help reach our aggressive goals for embodied GHG reductions in homes.

The Urban Stock in an Andean city and its comparison with coastal areas of Peru

Wednesday, 5th July - 09:15: Building & Infrastructure 3 (B0.13 KOG)

Ramzy Kahhat [1], ***Claudia Cucchi*** [1], ***Matias Gutierrez*** [1], ***Carlos Mesta*** [2], ***Samy Garcia*** [1], ***Alexis Dueñas*** [1], ***Johan Fellner*** [3]

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The importance of urban areas for society is undeniable and replicated around the globe, following different patterns that connect with cultural and socioeconomic aspects and necessities. The evolution of cities and the influence of these aspects can be understood when studying urban stocks. As an initial step to understand the difference in urban stocks, specifically building stocks, this paper explores the stocks of construction materials in the building sector of five urban areas of Peru, having the Peruvian Andes-bound city of Abancay as the center of the analysis and four urban areas on the coast (i.e., Chiclayo, Lince, Tacna, and San Isidro). All of them with different geographical locations, growth limits and socioeconomic levels. For this purpose, a bottom-up methodology has been selected as the main method.

Results show that the overall building stock in Abancay is around 110, a city that shows a decrease in the share of the Andes´ traditional material (i.e., adobe), the one that is replaced by masonry and concrete. While the agglomerations of Chiclayo and Tacna still include adobe in their urban stock, its distribution coincides with the peripheral of the cities, typically hosting low-income communities, and not necessarily the main used material in new constructions. By contrast, adobe is practically absent in more developed agglomerations, like Lince and San Isidro.

Only accounting for the residential sector, San Isidro presents the highest material stock per capita, while Chiclayo and Tacna, the lowest. Also, horizontal growth constraints, advancement and affluence of the former, generate a higher material stock that is also linked to required structural systems and parking space, the ones that may be replicated in other urban areas in the future.

Interestingly, each urban area shows a transformation of its building stock that can be linked to particular developments, some contemplated in socio-economic indicators (e.g., poverty index) and cultural aspects as well as the urban geographical or geopolitical limits.

Evaluating the Role of Embedded Materials in Fossil Fuel Infrastructure for the Energy Transition

Wednesday, 5th July - 09:30: Building & Infrastructure 3 (B0.13 KOG)

Yanan Liang [1]***, Sebastiaan Deetman*** [2]***, René Kleijn*** [3]***, Ester van der Voet*** [4]

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The mitigation of climate change requires massive and rapid transitions in the global energy system. Therefore, fossil fuels must remain underground while renewable energy is vigorously developed, and their demand must peak as soon as possible, or even decline for the foreseeable future. Consequently, the fossil-dominant energy infrastructure will be transformed and the future energy system will be very different from what we have today. Identifying the impact of system transitions on material use is an urgent priority. In studies conducted so far, materials needed for energy transition are primarily examined in the electricity and transportation sectors, and experts predict metal supply bottlenecks will almost certainly occur. However, there will be changes in the demand for fossil fuels resulting from the energy transition that is not limited to the end uses themselves. The upstream supply chain will also change, and low-carbon scenarios will require fewer fossil energy-related activities, including extraction, processing, transportation, etc. However, there is little research that fully captures the impact of the energy transition on material demand for upstream activities of the fossil fuel infrastructure (FFI). It is critical to understand how the shift to a low-carbon energy system will affect the demand for materials associated with these upstream activities.

Recognizing this gap, we develop an integrated global dynamic fossil fuel material model (FUMA) for the assessment of the material used for FFI. It would enable an assessment of the materials utilized at various phases of the FFI, along with how changes in demand for fossil energy will affect the requirement for such materials. We have also explored the possibilities for material circularity in the fossil fuel sector.

Society's material stocks as carbon storage: insights from a socio-metabolic perspective

Wednesday, 5th July - 09:45: Building & Infrastructure 3 (B0.13 KOG)

Lisa Kaufmann [1], *Michaela Theurl* [2], *Christian Lauk* [1], *Zhi Cao* [3], *Dominik Wiedenhofer* [1], *Helmut Haberl* [4]

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More than half of globally extracted materials are used to build up or renew societal stocks of buildings, infrastructure and machinery. This led to an accumulation of material stocks of 1064 Gt in 2015, representing a 26-fold increase throughout the 20th century. Construction materials such as concrete and asphalt account for the lion's share of material stocks. Simultaneously, the extraction and combustion of fossil materials, as well as industrial process emissions, disrupt biogeochemical carbon cycles resulting in an accelerating climate crisis. Therefore, the question of carbon stored in societal material stocks such as buildings and infrastructure enters the climate change mitigation debate.

Socio-metabolic research approaches these interactions between society and nature by quantifying economy-wide material and energy flows, as well as all the societal stocks encompassing the human population, livestock and all material stocks, e.g. buildings, infrastructure and machinery. Building upon the quantification of global material stocks presented in Krausmann et al. (2017) and Wiedenhofer et al. (2021), the socio-metabolic perspective leads to research interest in the respective carbon accumulation. Thus, we here present a time series of anthropogenic C stocks from 1900-2015 and seek to answer the following questions: how much carbon is stored by which material categories and over which timescales? How did socio-economic carbon stocks develop since the beginning of the 20th century and what are the dynamics and developments in nine different world regions in regard to the carbon stored in material stocks? We will present preliminary results indicating that similar to the accounting of material mass, construction materials represented the bulk socio-economic carbon stock in 2015. Solid wood products and plastics only represent a minor share of societal C stocks. Yet, due to their short lifetime, C flows leaving socio-economic stocks are dominated by materials that are connected to become emissions by combustion. Such carbon accounting contributes to completing global carbon budgets, informs national emissions inventories and contextualizes current climate mitigation strategies within a long-term perspective.

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Contaminant cycles in buildings and infrastructure: a case study on lead in PVC window recycling in Germany

Wednesday, 5th July - 10:00: Building & Infrastructure 3 (B0.13 KOG)

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Buildings and infrastructure (B&I) are the major physical capital of an economy and constitute the largest material stock of our society, which, in the case of Germany, amounts to around 340 metric tons of materials per capita. The use of plastics in buildings has been steadily increasing in the past and has led to a significant stock of plastic materials in buildings and infrastructure, with PVC (polyvinyl chloride) constituting the largest share of polymers in this sector. Whereas little plastic is yet recycled from construction and demolition waste, separate collection and recycling schemes exist for instance for PVC window frames. These recycling schemes are currently challenged by the presence of legacy contaminants in end-of-life window frames, in particular, lead-based stabilizers, which have been phased out in virgin PVC in Europe and are subject to use restrictions in new products. The long-lived nature of PVC window frames may therefore short-term threaten circularity targets. The goal of this study was to evaluate the current and future level of lead contamination in end-of-life PVC window frames in Germany and assess the effect of different restriction scenarios on closed- and open-loop recycling schemes for PVC window frames.

In a first step, a dynamic material stock and flow model for PVC on the goods layer and lead on the substance layer was developed for window frames in Germany. Next, various prospective scenarios were established to analyse the effect of different threshold concentration values of lead allowed in recycled PVC products (0.1%, 1%, no restriction), to account for EU circularity strategies in the B&I sector. The material efficiency of the PVC cycle was evaluated under the different scenario conditions and the effects on various recycling routes (closed- vs. open-loop) with respect to secondary PVC products were assessed.

The results of the dynamic stock and flow model showed that, despite the phase out of lead use in virgin PVC by 2015 in Europe, lead concentrations in EOL window frames in Germany will remain above 1% for more than another two decades and will drop below this concentration value around 2050. Recycled contents in PVC windows increased rapidly from 1% in 2000 to about 22% in 2021 with further development strongly depending on the applied restriction scenario. Whereas the 1% restriction on lead in new PVC frames would not pose a significant challenge to closed-loop PVC window recycling also in the future, this was not the case for the 0.1% restriction limit. In the latter case, more than half of the EOL PVC window frames collected for recycling could not be directed to recycling in the coming decades, but would have to either enter new recycling pathways including technologies for lead extraction or go to incineration.

The case study highlights the need to consider product residence times and stock evolution in order to develop efficient recycling schemes for plastic wastes in the B&I sector. As a next step, the model will be extended to evaluate the environmental performance of PVC window recycling and quantify potential trade-offs between material efficiency and environmental impacts using an integrated life cycle assessment framework.

Linking urban resource use, energy and emissions to urban typology and service provision: a conceptual framework

Wednesday, 5th July - 10:15: Building & Infrastructure 3 (B0.13 KOG)

Lisa Winkler [1], Stefan Pauliuk [1]

1. Freiburg University

Urban areas have been identified as a key focus area for climate change mitigation due to their high consumption of materials and energy and high greenhouse gas emissions [1]. Furthermore, there is a trend toward urbanisation with most cities globally expecting an increase in population [1]. This makes the prospect of carbon neutrality in cities difficult to imagine, as rising urban populations require a massive build-up of urban infrastructure and will lead to rising urban emissions if successful resource-efficiency and emission mitigation strategies are not applied. Previous research has shown demand-side solutions combined with improvements in technological efficiency to be key to curbing energy demand and providing a low-carbon transition to renewable energy [2]. However, sufficiency and low energy scenarios have been predominantly analysed on national and global scales [3, 4, 5]. These analyses yield estimates for resource use as well as energy and mobility demand that are aligned with the planetary boundaries, but they don't quantify how exactly changes in local buildings and transport can provide essential services with reduced consumption. Therefore, it is imperative to analyse local areas in order to identify city-specific mitigation strategies and to inform regional policy-making.

Strategies such as the repurposing of buildings, area-based insulation retrofits, local material sourcing and demolition-waste recycling, car-free zones, dynamic road user charging, public and active transport infrastructure, and more, are local in nature as their implementation depends on urban density, existing material stocks and infrastructure, as well as cultural behaviour and lifestyles. Moreover, personal income and attitudes affect user uptake and the contribution of such measures to social development goals, such as equality. To quantify the effect of such local changes in urban environments to resource use, emissions and energy demand and link it with social objectives, a bottom-up modelling framework which analyses the impact of changing local parameters is necessary. However, existing urban material flow and emissions models often lack spatial granularity and assume regional or local averages to compare cities against one another [6, 7]. Those that consider an urban area in high detail, do so for one case study only and fail to draw comparable conclusions, for example by developing archetypes of transformation in urban districts, which would allow for comparison between many cities and city-types.

Here we review the literature on existing spatial analyses of cities, focussing on the link between urban attributes, such as urban form and socio-demographic parameters, and energy demand. Regarding urban form, we investigate the density, diversity, connectivity, accessibility and material stock within cities, and regarding socio-demographic parameters, we investigate income and employment rate, as well as other possible parameters. We summarise the previously studied linkages between these respective attributes and the resulting mobility, space and heating/cooling demand and perform data scoping of available high-resolution urban data. We create a conceptual framework for a bottom-up model of urban resource use, energy demand and emissions, which explores bespoke policy mixes combining technological and demand-side solutions tailored to individual cities. We consider how well-being can be incorporated into the model to explore the co-benefits and trade-offs of resource-efficiency and climate change mitigation strategies.

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Integrating IE methods

Towards an Integration of Material Flow Analysis and Life Cycle Assessment Databases: an Efficient Estimation of Flows and Compositions in Ecoinvent.

Wednesday, 5th July - 09:00: Integrating IE methods (B0.41 KOG)

Han De Wachter [1], ***Guillaume Majeau-Bettez*** [1]

1. *CIRAIG, Polytechnique Montréal*

Life cycle assessment (LCA) is a crucial tool to guide decision making because of its ability to capture both direct and indirect impacts throughout the value chains. Ecoinvent is one of the leading databases that LCA studies use to represent different “background” activities and value chains in our economy. Ecoinvent contains fixed descriptions of processes and until now, the focus when constructing these processes lied on their linkages and the impacts they cause. The amount of material that is used to make a product was important, not the amount of material being wasted or incorporated into the final product. Material quality, dispersion, composition, and balance have not been systematically recorded or evaluated. With the current efforts to transition to a circular economy, material purity and the accurate calculation of impacts of material-focused strategies (recycling and downcycling) gain in importance. Despite the fact that product composition is largely unrecorded in the databases, there is evidence that the conservation of mass and of the different chemical elements is not respected. We propose a rebalancing algorithm which estimates the composition of all elementary flows and products in the different versions of the ecoinvent database by leveraging principles of material flows analysis (MFA). We aim to transform the ecoinvent database into a technologically rich MFA database. The algorithm reconciles fragmented data sources and ensures all activities comply with the conservation of mass principle. Because of the connected nature of the processes in our economy, the composition of all products and elementary flows must be calculated simultaneously. Otherwise, rebalancing one process could lead to imbalances in another due to heterogeneously aggregated product categories. An optimization problem thus forms, requiring the composition to differ as little as possible from preliminary data while complying with several constraints. The constraints include mass balance, conservation of the different chemical elements, and respect of lower and upper reasonable limits. This algorithm not only estimates the composition of flows, but it semi-automatically can identify potential missing flows, disaggregate heterogeneously aggregated flows, and flag major discrepancies. The main difficulties of this research are the limited amount of pre-existing data, the translation of the problem into an algorithm, the errors in the ecoinvent database and the requirement of mass and element balance necessitating different approaches for specific activity categories. We aim to contribute to the growing collection of opensource software tools of our research community.

MaLCAP: a flexible, open-source LCA-MFA process modelling framework

Wednesday, 5th July - 09:15: Integrating IE methods (B0.41 KOG)

Guillaume Majeau-Bettez [1]

1. CIRAIG, Polytechnique Montréal

Industrial processes are at the heart of industrial ecology (IE) research, notably in life-cycle assessments (LCA) and material-flow analyses (MFA). Nevertheless, LCA and MFA software tools struggle to support detailed models of processes capable of capturing their dynamics under different operating conditions (operation parameters, changes in feedstocks, etc.). In LCA, most processes are simply defined as “black boxes” — i.e., defined by the fixed ratios of their input and output flows with constant technical coefficients. Although some limited parameterization is now possible in LCA tools, capturing complex dynamics quickly becomes error-prone. In MFA, processes are typically represented with fixed transfer coefficients, which essentially limits modelling to linear responses to changes in feedstock. This simplicity in modelling is increasingly limiting for the IE community.

First, since technical coefficients in LCAs refer to ratios between flows, and transfer coefficients in MFA refer to ratios between materials (in flows and stocks), they can prove challenging to combine coherently in a single process model. This leads to the fragmentation of our modelling community.

Second, this inability to efficiently capture the life-cycle environmental consequences of changes in operation conditions essentially limits the extent to which we can guide process operations and optimization.

Third, the fixed coefficients and assumptions of homogenous (material) flows in LCA largely preclude our ability to quantify the environmental performance of processes working with a different feedstock than in the original inventory. This is particularly problematic for our community’s ability to guide circular economy initiatives, where recovered materials typically present different compositions and physical characteristics.

Fourth, this lack of parameterization and modularity of process models limits their reusability, leading to research inefficiencies. Because the deeper understanding of the mechanisms of the process is not embedded in the model, each novel situation (different environmental regulations, climate, geography, feedstock, etc.) requires either an independent inventorying effort or the use of uncertain proxies.

In response, we propose the MaLCAP framework: an open-source, MFA-LCA process modelling framework, with some very useful methodological innovations for the IE community:

MaLCAP’s first Python class is dedicated specifically to handling the different layers of composition of flows (elemental composition, mass composition, substance composition, products embedded in other products for dismantling, etc.) in a flexible and agile manner apt to represent heterogenous flows.

MaLCAP’s second python class (process.py) can “contain” models of any complexity, from black-box to full-fledged phenomenological engineering models, ensuring a smooth integration of different types models within a single LCA-MFA study. Beyond serving as a flexible container, this class is designed to structure and facilitate parameterization efforts by LCA/MFA practitioners:

- It provides extended definitions of technical coefficients, enabling flows to be scaled proportionate to any property of any other flow.
- It provides extended transfer coefficient definitions, allowing practitioners to specify under what form, and to what destination, each material from each input is transferred with a certain efficiency.
- It ensures a seamless reconciliation of technical and transfer coefficients, adjusting flow composition and magnitudes to reconcile these perspectives.
- It can reconcile overspecified models and estimate underspecified models with a flexible optimization approach, enabling an efficient support of studies with different levels of data richness.

This software is part broad push by our community to create flexible and powerful modelling platforms (notably Brightway2 and EASETECH) for more transparent, efficient, and reusable research.

Total Material Requirement (TMR) of Vehicle Production in China: Integrating Trade-linked Material Flow Analysis and Life Cycle Assessment

Wednesday, 5th July - 09:30: Integrating IE methods (B0.41 KOG)

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The electrification and lightweighting of vehicles increase the demand for mineral resources, including the direct inputs and indirect costs such as mine waste left on the ground. China has the world's largest electric vehicle market, severe environmental impacts have been caused on the mining location for China's vehicle production within the global trade network accordingly. Therefore, it is increasingly important to quantify the global environmental impacts of resource demand for Chinese automotive electrification and lightweighting.

Total material requirement (TMR) has been used as an aggregated indicator to reflect the total mass of primary materials extracted from nature, including hidden flows such as mine waste. Existing literatures have greatly contributed to quantifying TMR in various industries in many countries. The multi-regional input-output is usually applied to calculate TMR caused by the economy-wide international trade among several regions. However, it cannot sufficiently reveal the detailed material flows in each process, and the industry classifications were often based on many assumptions. At the same time, the comprehensive environmental implications on China's vehicle production were rarely noticed.

Therefore, this study aims to establish a new TMR database for China's vehicle production by integrating trade-linked material flow analysis (MFA) and life cycle assessment (LCA). The trade-linked MFA model was applied to simulate vehicle production resource flows, and LCA was used to estimate the resource input for each process. Five key life cycle stages (mining, beneficiation/ evaporation, smelting & refining, fabrication, and manufacturing) and three kinds of flows (domestic, international trade of raw materials and semi-products, and other regions) are defined. In addition, up to ten critical ore resources (Fe, Al, Cu, Ni, Li, Mg, PGMs, Pb, Co, REEs) and three energy resources (coal, oil, natural gas) for vehicle production are considered.

We have considered 815 mine sites relevant to China's vehicle production, including 601 coal mines, 70 Fe ore mines, 56 bauxite mines, 35 Li mines, 33 Ni mines, and 20 Cu mines. Among all these ores, bauxite has the largest TMR coefficient, with 7.4 t of solid materials would be produced from underground mines to produce 1 t of bauxite. On the other hand, cathode Cu has the largest TMR coefficient among semi-products because of the production process's low grade of Cu ore and large loss rate.

The results suggested noticing the embodied and increasing environmental impacts from the more complex global trade networks and the increasing demand for Al, Cu, and Ni. Furthermore, it presented an explicit TMR picture of China's vehicle supply chain by establishing an updated and extended TMR database. We believe our results will provide broad policy implications for sustainable vehicle production management and mitigating global environmental pressure in China's green transition.

Life cycle risk assessment framework as an integrative method to establish effective solar technology companies worldwide

Wednesday, 5th July - 09:45: Integrating IE methods (B0.41 KOG)

Angela Ciotola [1]***, Richmond Kuleape*** [2]***, Maryegli Fuss*** [1]***, Witold-Roger Poganietz*** [1]***, Simone Colombo*** [3]

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Emerging or conventional solar technologies are drivers for progress to deploy renewable energy worldwide. According to the development principles, the wishes and needs for solar technologies are often taken from country to country. The research and innovation (R&I) perspective, fastest market growth of conventional solar technologies and climate oriented-policies made Germany an example country of implemented systems on roof-tops, facades and ground-mounted plants. The positive German influence, for example, creates global connections for spreading the advantages of solar systems in the Global South. For instance, the climate conditions make African countries seek or become partners for global climate actions (sustainable development goal, SDG 13) and affordable and clean energy (SDG7). Beyond ground-mounted systems, innovative systems are promising for African countries, such as agrivoltaics piloted in Kenya and Rwanda.

Although more start-ups are focused on emerging technologies in Germany (e.g., Organic Photovoltaics and Perovskites) or conventional ones (e.g., solar street lighting and solar tricycle) to assist system innovation in Africa, the raw material supply chain rises as a global problem. Several studies usually present sustainability and social issues as indicators because of mining conditions in Congo, for example. In this matter, life cycle assessment (environment, social and economic) helped to bring numerical awareness. However, a holistic view of the risk factors is still demanded to assist R&I and start-ups in establishing effective and sustainable solar technologies worldwide. This study integrates the principles of life cycle thinking and risk assessment to develop a modelling approach to support companies worldwide to lead with local to global problems. Thanks to the Holistic Risk Analysis and Modelling (HoRAM) method, it was possible to collect and study the logic and stochastic interconnections, meant as cause-effect links, among more than 500 variables related to the supply chain of raw materials.
HoRAM, a decision engineering approach based on the Artificial Logic Bayesian Algorithm, is a logic-based method that allows performing dynamic logic-stochastic simulations that generate scenarios in the form of readable stories, each coupled with a probability of happening and an impact value. Moreover, it allows considering variables of both qualitative and quantitative nature. For this study, a general model structure was created to adapt the indicators' impacts and probabilities based on the selected raw materials and the countries involved in the supply, the ones who are importing, exporting and refining the material. The modelling outputs are:

- the entire universe of possible scenarios,
- the risk curves and spectrums of the overall system,
- the list of the critical variables on which it is needed to act to reduce the risk associated with the process,
- the expected cost of the supply,
- the expected environmental impact of the process,
- the probability of disruption of the material supply from the analysed country.

The models created can assist researchers and start-ups in assessing potential impacts and risks during the project life cycle.

The modelling is tested through two use-case scenarios involving agrivoltaics for the sub-Saharan African countries, namely Ghana and Congo. The silicon supply chain is assessed in terms of costs, environmental impact, probability of material disruption, and social acceptance to support the decision-making process in the investment of solar panels manufacturing for agrivoltaic development in emerging economies. Germany, in this case, is considered to be the investing institution and the knowledge owner partner of the project.

Exploratory System Dynamics Modelling and Analysis of Metal Supply Chains

Wednesday, 5th July - 10:00: Integrating IE methods (B0.41 KOG)

Jessie Bradley [1]***, Benjamin Sprecher*** [2]***, René Kleijn*** [3]***, Jan Kwakkel*** [1]***, Willem Auping*** [1]

1. *Delft University of Technology,* ***2.*** *Technical University Delft,* ***3.*** *Leiden University, CML*

Metal supply chains are part of complex systems that are constantly evolving over time. Traditional industrial ecology tools such as Material Flow Analysis (MFA) and Life Cycle Assessment (LCA), and assessments of material circularity and criticality, often provide static snapshots of metal systems. Such approaches are useful for identifying short-term challenges and opportunities, but fail to capture certain risks and possibilities of longer-term developments such as the energy transition. System Dynamics (SD) modelling is a valuable tool for capturing such dynamic complexity. It provides insights into future demand projections, but also into the ability of supply to keep up with demand, through the inclusion of feedback loops, delays and accumulations. Existing SD models of global metal supply chains have a high level of aggregation. In contrast, we are developing a model that includes geographical and sectoral disaggregation. This model incorporates MFA and LCA elements in a prospective dynamic manner, and is able to determine regionally and technologically specific supply chain losses, recycling rates, product lifetimes, sustainability impacts, and supply risks, based on changing sectoral shares and regional concentration of primary and secondary production over time. We can use the model to test the impacts of various disruptions, such as geopolitical disturbances, societal crises, and radical innovation. We can also use the model to test the impacts of various policies and strategies for improving supply chain sustainability and resilience. The model can highlight trade-offs and interferences between these strategies, which is essential for making informed decisions that balance environmental, economic, and social considerations. We combine the model with Exploratory Modelling and Analysis (EMA) by exploring a large number of possible futures that include various structural and parametric uncertainties. The resulting Exploratory System Dynamics Modelling and Analysis (ESDMA) provides a comprehensive approach to understanding the potential future developments of global and regional metal supply chains and what can be done to improve their sustainability and resilience.

Mat-dp: An Open-Source Material Demand Projections Model and its Application To Energy and Transport

Wednesday, 5th July - 10:15: Integrating IE methods (B0.41 KOG)

Karla Cervantes Barron [1], ***Jonathan Cullen*** [1]

1. *University of Cambridge*

The transition to low-carbon systems requires more and more specialised materials. The materials include bulk ones such as steel or cement, and critical ones such as lithium or rare earths. Since these systems will be built in many countries, with varying degrees of industrialisation, assessing material demand to inform national strategies is essential. This will support a transition where emissions from material production are considered and risks in material supply chains may be mitigated.

In response, this study introduces a purpose-built open-source model called MAT-dp (Material Demand Projections)[1]. The main aim of Mat-dp is to determine the types and quantities of different materials needed for energy and transport systems. Once these are determined, Mat-dp allows for other material implications to be explored such as material criticality scores, and environmental and/or socioeconomic implications.

The open-source parts of Mat-dp include an optimisation tool for material demand, a database with material intensities, a tool to integrate energy or transport model results to Mat-dp, and a user-friendly interface to visualise results. These parts aim to help modellers, country-level planners or decision makers to identify the materials they will need for planned systems and inform strategies surrounding industry, trade or supply security. Mat-dp is designed for both expert users who are comfortable with coding and for less-experienced users through the use of the visualisation tool. Mat-dp was made open-source so that different systems and scenarios could be explored in any country, thus enabling quick assessments to be made to make decisions.

This study will highlight how Mat-dp can be used, its key underlying assumptions and how to change them, how users can apply the model to new scenarios, how users may contribute to Mat-dp, and some inspirational examples to date. The key assumptions will include the technology change rates, upper and lower bounds and recycling rates. The examples to showcase include several Global South countries (e.g., in African countries [2] or in different Asian, African or Latin American countries [3]).

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Social Dimensions 3

Regional Structure, Inequality, and emission scenarios of India's household consumption of food, electricity, transport, and clothing needs.

Wednesday, 5th July - 09:00: Social Dimensions 3 (B0.16 KOG)

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Abstract: Addressing inequality and increased well-being goals for 1.4 billion people in a carbon-constrained future is going to be a formidable challenge for India. Herein, we analyze the carbon emissions associated with the food, clothing, transportation, and energy needs of Indian households to assess the level of disparity between urban and rural regions. Further, we explore how policy-supported supply-side transitions and class-dominated demand-side reductions can lower the impacts in the future.

Methodology: We utilize India's 2011-12 consumer consumption data for 12 expenditure classes in 35 different states and union territories (UTs) with carbon emission intensities of products and services accounted within food, clothing, transport, and energy categories to estimate the class-dominated regional household emissions. For scenarios, we evaluate impact reduction from expansion of renewable energy infrastructure, pursuing nutrition-security, and reduced travel of travel-dominant expenditure classes, while excluding the rebound impacts and regional supply chain emissions. Within these scenarios, we explicitly excluded the role of EVs and clean cooking stoves since both pathways will likely embody carbon costs (and other environmental impacts) elsewhere in the lifecycle.

Results: At the national level, we estimate average per capita emissions of urban population are higher (2.7 tCO2eq) compared to those of rural areas (2.2 tCO2eq). However, due to a larger share of the population, the rural areas contributed two-thirds of total national emissions, equivalent to 2.6 GtCO2eq. Among product categories, fuel and lighting, transportation, milk and dairy, meat and egg, and rice contributed 1020, 280, 610, 430, and 130 MtCO2eq, respectively. The highest inequality is observed for transportation with the top four expenditure categories contributing 72%, followed by animal-based diets.

At the state level, the highest per capita emissions were seen in UTs, and northern states, including Haryana, Delhi, Himachal Pradesh, and Jammu & Kashmir, followed by southern states of Goa, and Kerala, among others. Per capita of the most populated states, including Uttar Pradesh, Bihar, Maharashtra, Madhya Pradesh, and Chattisgarh, among others were on the lower end. However, at the aggregate level most populated states including Rajasthan and Gujarat had the highest total emissions. The highest inequality was seen in the UT of Lakshadweep, states of Arunachal Pradesh, Haryana, Uttar Pradesh, Madhya Pradesh, and Goa, among others.

Accounting for rural-to-urban migration, population growth, and different economic growth projected for individual states, future scenarios of food and non-food categories display significant deviations till 2050. The per capita food emissions are expected to grow in states moving towards animal-based diets, such as Haryana, Mizoram, and Kerala; whereas, highest non-food emissions increase were foreseen for Mizoram, Gujarat, and Haryana due to increased use of personal vehicles and higher electricity consumption if their economies continue to grow as projected. Under BAU, we foresee national average per capita emissions could be around 6.3 tCO2eq for urban and 5.7 tCO2eq for rural areas in 2050.

Investigating the impact of transitions, we estimate that higher penetration of renewables, especially solar, would substantially reduce cumulative emissions till 2050; however, the impact of animal-based diets (milk, meat, etc.) could exceed India's food carbon budget if the population adopts such diets. We further estimate

that if the top-four expenditure categories were to reduce their travel by 1% per annum, their emissions could be reduced by a third.

Interdependencies of circular economy measures and societal inequality in the European residential building sector

Wednesday, 5th July - 09:15: Social Dimensions 3 (B0.16 KOG)

Christian Hauenstein [1], ***Stefan Pauliuk*** [2]

1. *University of Freiburg,* ***2.*** *Freiburg University*

The buildup and operation of in-use stocks, such as cars and residential buildings, is responsible for large shares of resource use and causes about one third of annual global greenhouse gas (GHG) emissions.[1] However, the per capita ownership and use of these stocks is distributed unequally among socio-economic strata within and in-between countries.[2,3] Circular economy (CE) strategies can contribute to lower resource consumption and GHG emissions from in-use stocks. However, socio-economic conditions of in-use stock users might affect the implementation and effectiveness of CE measures,e.g., if the financial means of stock owners to realize CE measures are missing.[4] Furthermore, it needs to be ensured that CE measures do not aggravate socio-economic inequalities,e.g., by increasing housing costs for low income households.[5] Thus, to assess the effectiveness and mitigation potential of policies aiming to implement CE measures, as well as effects on societal inequalities, it is necessary to take into account socio-economic inequalities of in-use stock users and ultimately, a co-design and co-implementation of policies aiming at environmental and social sustainability.

In this study, we use and enhance an open-source and modular dynamic material flow analysis model (RECC, resource-efficiency and climate-change model),[6] to study the effect of socio-economic conditions of stock users on the implementation of CE measures, and vice versa, in the residential building sector in the European Union (EU). We implement a socio-economic dimension in the RECC's residential building sector, which allows to differentiate the service provision of different segments of the residential building stock (e.g., building types and age) to societies' socio-economic strata. Thus, we assess the effectiveness and effects of different CE policy scenarios in the EU. We present the conceptual framework of the CE-inequality analysis, the available data, the extension of the RECC model, and some first stylistic results. Our main contributions are twofold: first, We provide a better understanding of the challenges and opportunities in the design of CE policies and measures in the residential building sector. Second, we discuss the implications of societal inequality on sustainability transformations, and vice versa.

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Inequality redistribution in eco-social policy narratives.

Wednesday, 5th July - 09:30: Social Dimensions 3 (B0.16 KOG)

Sam Betts-Davies [1]***, John Barrett*** [1]***, Paul Brockway*** [1]

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In descriptions of a socio-ecologically sustainable future, ensuring a decent quality of life whilst remaining within planetary boundaries are often dual central aims. However, at present no country is achieving this. In response, the need to reduce socio-economic inequality is increasingly highlighted in climate mitigation proposals, spanning a broad range of eco-social narratives, including Green Growth, Green New Deal and Post-Growth proposals. Despite this broad support for inequality reduction, the relationship between inequality and planetary boundaries is complex and understudied, particularly with regards to the climate impact economic inequality reduction may have in these divergent eco-social policy narratives. Through a structured integrative review of academic literature that discusses inequality reduction alongside these narratives, this paper unpicks the prevalence of, motivations for and mechanisms through which socio-economic inequality reduction may be achieved. Whilst this review finds that inequality reduction features widely across all narratives, the purposes for and mechanisms through which inequality reduction is to be achieved are often distinct. It is argued that these are likely to incur significant differences in the climate impact of ensuring decent living standards under each eco-social narrative. Despite this, little investigation is given to these impacts within any of the narratives, indicating the need for further empirical investigation of this important tension in eco-social research.

Just and Sustainable Urban Systems - Urgent Research Priorities

Wednesday, 5th July - 09:45: Social Dimensions 3 (B0.16 KOG)

Melissa Bilec [1], ***Joe Bozeman III*** [2], ***Hua Cai*** [3], ***Shauhrat Chopra*** [4], ***Oliver Heidrich*** [5], ***Kangkang Tong*** [6]

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Our changing climate and associated weather damages present not only challenges but also opportunities to maintain, design, and reimagine just and sustainable urban systems. The challenges highlight inequitable and unjust barriers. The International Society of Industrial Ecology (ISIE) Sustainable Urban System (SUS) board members and colleagues have identified and recently published research priorities for just and sustainable urban systems, aiming to address resource inequities and injustices and advance urban systems. The three research priorities are: (1) social equity and justice, (2) circularity, and (3) digital twins and are in support of the United Nations Sustainable Development Goals of No Poverty, Decent Work and Economic Growth, Reduced Inequalities, Sustainable Cities and Communities. In this talk, we will discuss each priority in terms of context and research directions. For socialequity and justice, we discuss historical injustices, equity analysis and inclusionary practices, and diverse stakeholder engagement. For circularity, a discussion on just circular economies will be presented, along with the need for advanced metrics, robust evaluation frameworks, and dynamic modeling across spatial and temporal scales. Lastly, for digital twins, we will focus on complexity, integration, and reducing barriers to data access. Throughout the talk, we will focus on local efforts and community-engaged research.

Burden of the global energy price crisis on households

Wednesday, 5th July - 10:00: Social Dimensions 3 (B0.16 KOG)

Jin Yan [1]***, Yuru Guan*** [1]***, Yuli Shan*** [2]***, Klaus Hubacek*** [3]

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Energy markets have tightened since the COVID-19 pandemic and the situation was exacerbated considerably following the Russia-Ukraine conflict in late February 2022, contributing to a global energy crisis. High energy prices impose cost burdens on households in two ways. On the one hand, fuel price rises directly increase household fuel bills (e.g., for heating and cooling, cooking, and mobility). On the other hand, energy and fossil feedstock inputs needed for the production of goods and services for final household consumption will lead to higher prices of household expenditure items. Here we conduct a global comparative analysis of household burden across consumption levels under a set of price scenarios triggered by the Russian-Ukraine conflict. By linking a highly detailed expenditure database to a global multi-regional input-output database, we model the direct and indirect burden of increased energy prices on households with different consumption patterns. We distinguish between 201 expenditure groups in 116 different countries, covering 87.4% of the global population, with a focus on developing countries.

Based on a set of energy price scenarios, we show that total energy costs of households would increase by 62.6-112.9%, contributing to a 2.7-4.8% increase in household expenditure. The energy cost burdens across household groups vary due to differences in supply chain structure, consumption patterns, and energy needs. Comparing across countries, households in Central Asian countries are most affected in terms of total energy cost, and Sub-Saharan African countries are most affected in terms of total energy cost burden rate (the energy cost as a percentage of total household expenditure). Wealthier households tend to have heavier burden rates of energy costs in low-income countries, whereas poorer households tend to have higher rates in high-income countries. Under the cost-of-living pressures, an additional 78-141 million people will potentially be pushed into extreme poverty. Targeted energy assistance can help vulnerable households during this crisis. We emphasize support for increased costs of necessities, especially for food.

“The Great Stagnation”: Reflection on historical growth in a WISE view

Wednesday, 5th July - 10:15: Social Dimensions 3 (B0.16 KOG)

Kedi Liu [1], ***Ranran Wang*** [1], ***Rutger Hoekstra*** [1]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden

The Great Acceleration, a period of rapid economic and material growth since the 19th century, particularly from the mid-20th century to the present, has brought prosperity and wealth accumulation. However, when viewed from a well-being perspective, is this acceleration truly beneficial or it is “the Great Stagnation”? The unchecked growth in GDP has led to environmental crises such as climate change, excessive exploitation of nature, and loss of biodiversity. Data reveals a significant increase in CO2 emissions (625 times) compared to GDP growth (12 times) between 1820 and 2018. The industrial progress of the 20th century resulted in detrimental effects on human health and biodiversity, as evidenced by pollution events like the one in London that claimed lives.

Economic expansion has given rise to millionaires and billionaires, accompanied by income inequality. Numerous studies have demonstrated that highly uneven wealth distribution is associated with lower well-being indicators, such as increased homicide rates and resource inequality across societies globally. From 1820 to 1992, global total inequality rose from 0.4 to above 0.8, while inequality between country groups increased from negligible levels to 0.5, and within country groups, it decreased by 0.1.

In this research, we introduce several Wellbeing, Sustainability, and Inclusion (WISE) indicators to analyze the historical development trends during the “Great Acceleration” period worldwide. At a global scale, the gender equality index, which combines various social aspects, only increased from 59.4 in 1950 to 68 in 2003, indicating significant gender disparities persist across countries. The Human Development Index (HDI), a composite measure encompassing health, income, and education, shows impressive progress, almost doubling from 1950 to 2020, with life expectancy being the major contributor. The Composite Measure of Wellbeing, incorporating societal, economic, and health variables, increased from -0.49 to 1.47 between 1820 and 2000. Country profiles demonstrate uneven distribution of well-being and evolving patterns worldwide, with developed countries accumulating wealth while disparities persist in other nations.

Considering the future promotion of beyond-GDP measurements, it is crucial to adopt such measures to assess historical trends. Reflecting on the concept of the “Great Stagnation,” we are not suggesting a return to a primitive world or abandoning modern achievements. Instead, we emphasize the importance of considering overall well-being for human society and our planet beyond simple economic growth as we reflect on the past.

Special Session:
Low-Carbon Lifestyles to Meet the 1.5°C Target

PROJECTING HOUSEHOLD CARBON FOOTPRINTS IN 2030 AND 2050 BY ADAPTING SUPPLY AND USE TABLES FOLLOWING SHARED SOCIO-ECONOMIC PATHWAYS

Wednesday, 5th July - 11:00: Special Session: Low-Carbon Lifestyles to Meet the 1.5°C Target (A0.51 KOG)

S. Cap [1], *Arjan de Koning* [2], *L. Scherer* [1]

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Scenarios that limit global warming to 1.5°C rely on a combination of mitigation options to meet emissions reduction targets. The most ambitious emissions reduction pathways include widespread technological change, such as the adoption of renewable energy, deployment of carbon capture and storage and overall efficiency improvements across economic sectors. The share of climate change mitigation necessary from technological or behavioural change has generally been studied from a static perspective and thus does not account for how the need for mitigation from behavioural change evolves following possible economic and technological developments. In this study, which is a part of the H2020 project “EU 1.5° Lifestyles”, we calculated the remaining mitigation necessary from lifestyle changes (or negative emissions technologies) even with extensive technological transformation.

This study adapted a global supply and use table framework from EXIOBASE 3 in line with existing climate change scenarios to create scenario models of how consumption-based footprints will evolve by 2030 and 2050. The exogenous changes applied for each scenario are the basic elements from Shared Socio-Economic Pathway 1 (SSP1) and technical changes consistent with lower levels of anthropogenic forcing as modelled by the integrated assessment model IMAGE. Direct and second-order adjustments from balancing were implemented consecutively for changes to population, gross domestic product, economic structure, total factor productivity, electricity generation mix, electrification and biofuel uptake in the transportation sector, fuel shifts for space heating and manufacturing sectors, and adoption of carbon capture and storage by industry. Changes conceivably linked to behaviour change, such as household adoption of electric vehicles, were excluded to isolate the effects of technological shifts. After converting the adapted supply and use tables to a multi-regional input-output model, shifts in household final demand expenditure from increasing wealth were modelled by adjusting final demand spending following income elasticities of demand. The resulting scenario models were used to assess the extent that technological change alone can mitigate greenhouse gas emissions in the 44 countries and 5 Rest of World (RoW) regions covered by EXIOBASE 3. To assess compatibility with a 1.5°C scenario, we calculated household emissions targets from the median annual emissions in 2030 and 2050 for models following a 1.5°C trajectory and divided this equally per capita for the global average share of household emissions over the scenario period.

In 2030, the only regions remaining on a 1.5°C trajectory without additional efforts are India, Slovakia, RoW Africa and RoW Asia. By 2050, no countries are projected to meet a 1.5°C-compatible target with only background system emissions reductions. Average global household emissions decrease from 3.56 tCO_2e/cap in 2015 to 3.15 tCO_2e/cap in 2030 before peaking at 4.01 tCO_2e/cap in 2050. We estimated that without further household intervention, the average global overshoot for household emissions will be 0.85 tCO_2e/cap in 2030 and 3.50 tCO_2e/cap in 2050. If rising incomes lead to additional household fuel demand, following past trends and our modelling assumptions, household direct emissions will be a major challenge for decarbonization due to the sharply rising share of direct emissions in total household emissions.

Our results demonstrate the importance of behaviour change in climate change mitigation. Further research can quantify the amount of behaviour change options needed to stay within the aspirational 1.5°C target proposed in the Paris Agreement.

Assessing the Potential of Lifestyle Changes for a Low-Carbon Society: A Cross-Country Survey and Input-Output Analysis Approach

Wednesday, 5th July - 11:20: Special Session: Low-Carbon Lifestyles to Meet the 1.5°C Target (A0.51 KOG)

Roberto Vaccaro [1], Abigail Alexander-Haw [2], Aurore Flipo [3]

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The purpose of this presentation is to share the findings of the carbon footprint survey currently being conducted as part of the Horizon 2020 project Fulfill, to explain how they will be utilized to evaluate the overall impact of lifestyle changes at the European level by applying Input-Output methods, and to compare the two different approaches with regard to the quantification of emissions. The project Fulfill, by linking the empirical research shaped by social sciences and humanities with prospective studies in the field of energy and climate scenarios and comprehensive impact assessments, aims at providing insights and quantitative data for the evaluation of the potential contribution of lifestyle changes towards a low carbon society and the development and update of the Nationally Determined Contributions (NDCs) to be submitted in 2025.

While many earlier studies have surveyed household engagement in sustainable behaviours, relatively few have done so based on a systematic cross-country comparison using representative samples. Furthermore, few studies have focused specifically on sufficiency lifestyles, and none have used quantitative measures for actual climate impact. The study addresses these gaps by conducting a cross-sectional survey in five countries (Latvia, Germany, France, Denmark, Italy), which includes a carbon footprint assessment that separates individuals into five groups: very sufficient individuals, sufficient individuals, individuals with low carbon footprint and low well-being, individuals with average carbon footprint and individuals with very high carbon footprint. The survey results identify critical lifestyle changes needed for respondents to achieve a low-emission lifestyle under different assumptions of low-emission solutions.

The Fulfill project aims to utilize the survey results, along with other findings from the project, in empirical meso-economic approaches based on Input-Output analysis (IOA) to determine the potential economy-wide and climate impacts associated with scaling up sufficiency measures and lifestyle changes assessed at the European level.

The presentation will cover the methodological aspects underlying the Input-Output approach, including the choice of database and challenges involved in transforming survey data and other SSH analysis from the project into quantitative shocks for the Input-Output model. Additionally, the presentation will discuss the relevance, novelty, and criticalities of the approach and its comparison with other modelling approaches in light of the findings from the latest IPCC report on the contribution of lifestyle changes. Finally, the presentation will also include a comparison of the emission quantification approaches used in the survey and Input-Output analysis. Overall this presentation will provide insights into the potential of lifestyle changes to contribute to a low-carbon society and the challenges involved in measuring and quantifying their impact.

THE CLIMATE PUZZLE – A TOOL FOR PLANNING 1.5-DEGREE LIFESTYLES

Wednesday, 5th July - 11:35: Special Session: Low-Carbon Lifestyles to Meet the 1.5°C Target (A0.51 KOG)

Jari Kolehmainen [1], *Michael Lettenmeier* [2]

1. d-mat ltd, 2. Aalto University

The Climate Puzzle is a design and educational game developed by D-mat ltd and based on micro-level life-cycle data. Its purpose is to help households and other stakeholders to understand the concepts, opportunities and challenges of 1.5-degree lifestyles (IGES, 2019; Akenji et al., 2021), and to provide concrete ideas and measures that inspire the transition towards low-carbon lifestyles. The Puzzle also fosters discussion and action around the systemic changes required to enable 1.5-degree lifestyles.

In the Climate Puzzle, a person or household first seeks to fill the gap between their present lifestyle carbon footprint (measured with a web-based calculator) and the 1.5-degree lifestyle target of 2.5 tonnes CO2e for 2030. The gap is filled with options reducing carbon footprints. The Climate Puzzle contains appr. 90 different options printed on appr. 130 cards of four different colour (for the consumption domains of nutrition, housing, mobility and other) and four different sizes (representing the carbon footprint reduction potential of the option on the card). After having filled the mentioned gap with cards, the cards are reorganized on a timeline from the present moment to the year 2030, thus making a plan for adopting one's lifestyle towards the 1.5-degree climate target of the Paris Agreement. In the next step, the Climate Puzzle guides its user to plan experiments for reducing their lifestyle carbon footprint. Finally, the user is guided to consider, how the public infrastructure and services as well as companies' offering have to change in order to ease or accelerate people's transition to low-carbon lifestyles.

The original Climate Puzzle has been developed for Finland and is nowadays available in Finnish, Swedish and English. An own version for Germany has been published in early 2023. In a Horizon2020 project called EU1.5Lifestyles (onepointifivelifestyles.eu) an adapted version of the Climate Puzzle has been produced on the basis of input-output-based calculation for appr. 50 options reducing lifestyle carbon footprints. This version has been used in Citizen Thinking Labs and Stakeholder Thinking Labs in the case countries Germany, Spain, Hungary, Latvia and Sweden in order to find out preferences, enablers and barriers for mainstreaming 1.5-degree lifestyles. In Finland the original Climate Puzzle has been applied in citizen workshops and Sustainable Lifestyles Accelerators organized by D-mat, municipalities and others, with a total amount of more than 500 participants so far. Prototypes of the Climate Puzzle have earlier been tested also in Japan, Germany, Spain, Switzerland, Mexico and India.

Our experiences imply that the Climate Puzzle has been successful in enabling the participants to (a) understand the global climate targets in relation to their own lives, (b) perceive the variety and scale of multiple options for reducing carbon footprints, (c) develop pathways towards low-carbon lifestyles, and to (d) identify options that they can implement directly. The game can also be used in creating a learning space for enhancing stakeholder collaboration and dialogue.

(PATH)WAYS TO SUSTAINABLE LIVING: THE INTENT AND IMPACT OF THE SLIM SCENARIOS ON LONG-TERM EMISSIONS

Wednesday, 5th July - 11:50: Special Session: Low-Carbon Lifestyles to Meet the 1.5°C Target (A0.51 KOG)

Nicole van den Berg [1], ***Andries Hof*** [1], ***Detlef van Vuuren*** [1], ***lewis akenji*** [2], ***Vanessa Timmer*** [3], ***Nicole-anne Boyer*** [4]

1. *Utrecht University*, ***2.*** *Hot or Cool Institute*, ***3.*** *OneEarthLiving*, ***4.*** *NOW Partners*

Sustainable lifestyle changes can play a critical role in climate change mitigation. This presentation illustrates a set of four comprehensive sustainable scenario narratives, collectively named Sustainable Living in Models, or SLIM, scenario narratives. These narratives describe different alternative pathways in which lifestyle changes may unfold towards 2050 and can support strategic dialogue or form the basis for model-based scenario analysis. The four SLIM scenario narratives, Designed World, Global Commons, Big Village and Pocket Lifestyles, emerged from multidisciplinary workshops with lifestyle change experts, scenario analysts and integrated assessment modellers. The narratives diverge along two critical uncertainties: focus on individual versus communal values and the level of access to centralised vs. distributed support for the transition to sustainable lifestyles. These SLIM scenario narratives present a richer understanding of the role that sustainable lifestyles could play in climate change mitigation. The SLIM scenario narratives emphasise the role of society, enablers, lifestyles *and* behaviours in systems change. In this presentation, I will also describe the SLIM scenario narratives in terms of contrasting characteristics. I will also touch upon the various levels of changes within each scenario narrative through the themes: individual agency, technology support, the pace of life, social equity, security and safety, public/private/community, and speed and depth of transition. The speed and depth are the basis for the modelling assumptions, influenced by the other themes. The SLIM scenario narratives support a greater understanding of the role of sustainable lifestyles in climate change mitigation while providing less-stylised assumptions for model-based scenarios. The enduring impact of this process is through a longer-term research programme attracting a burgeoning community of practice with modellers and sustainable lifestyle practitioners. Most notably, the narratives can allow for strategic discussion and action for policymakers.

BEHAVIOURAL CHANGE FOR THE CIRCULAR ECONOMY AND ITS IMPACTS AT THE REGIONAL AND CITY LEVELS

Wednesday, 5th July - 12:05: Special Session: Low-Carbon Lifestyles to Meet the 1.5°C Target (A0.51 KOG)

Olga Ivanova [1]

1. *PBL Netherlands Environmental Assessment Agency,*

Policies that promote 'going circular' decisions by consumers are most effective if they are designed to address factors shaping individual behaviour, according to the new EEA briefing 'Enabling consumer choices for a circular economy' . The briefing looks at how policies can enable more circular-economy friendly consumer behaviour by understanding the factors that influence it. Promoting circular decisions contributes to reducing the use of materials and energy and leads to reduction of global CO2 emissions.

Social factors, preferences and beliefs touch upon individual psychology and are thus considered the most difficult to influence or change by policies, as our values and norms are created by the processes that shape our personality. Policymakers generally perceive that it is difficult to change social factors, personal beliefs and attitudes through policy tools. Private sector marketing strategies aim to shape these factors through long-term approaches and tools such as advertising or using social media influencers, often promoting linear product solutions (e.g. fast fashion).

Understanding the impacts of individual behaviour in the context of circular economy requires methodological and modelling tools that go beyond the existing micro and macro-economic approaches and that are instead embedded into the behavioural theories, models, and intervention tools that are linked to sustainable consumption and pro-environmental behaviours. There have been a number of interesting theoretical papers applying existing behavioural theories to circular economy. However the literature is missing sound empirical models that start from these theories and build on existing data (for example various surveys) to translate them into theory-based empirical models that can be used for the assessment of behavioural changes related to circular economy, and possibly also some of the relevant policy options.

We can make use of the discrete choice models that are able to address both monetary and non-monetary attributes of the products or options as well as take full account of the complex heterogeneity of consumers. The outcomes of empirical discrete choice models could be further integrated with more classical regional economic models such as MRIO and SCGE models (EU-EMS model of PBL) in order to assess broader regional-economic and sectoral impacts of the behavioural changes as well as to take into account the relevant micro and macro-level rebound effects.

Special Session: Industrial Ecologists in a world in Turmoil

Special Session: Securing raw materials supply for electric vehicles Part 2: Sourcing the battery raw materials of tomorrow - Impact on mineral supply chains

The battery demand for nickel creates supply bottlenecks and problem shifts, and increasing emissions

Wednesday, 5th July - 11:00: Special Session: Securing raw materials supply for electric vehicles Part 2: Sourcing the battery raw materials of tomorrow - Impact on mineral supply chains (B0.17 KOG)

Eric Young [1]***, Romain Guillaume Billy*** [2]***, Fernando Aguilar Lopez*** [2]***, Daniel B. Müller*** [3]

1. SINTEF Oceans, 2. Norwegian Univ. of Science and Technology, 3. Norwegian University of Science and Technology

Nickel has historically been a major metal with established supply chains, mainly to produce stainless steel. However, the demand for nickel is rapidly increasing due to its use in lithium-ion batteries for electric vehicles, creating pressure on the different stages of the supply chain of this critical raw material.

This work considers different scenarios for the supply and demand of nickel in batteries and non-battery applications up to 2050. Using a demand-driven supply-constrained dynamic material flow model, we analyze how the growing demand for nickel to batteries can be met in the future, the potential bottlenecks in the supply chain, and the consequences on GHG emissions from different nickel mining and refining production routes.

We did not identify major risks of supply disruption for nickel. However, our results show a large variation in the characteristics of production routes. Production routes that are faster to develop, like nickel pig iron (NPI) smelting, are also the ones that have the highest carbon footprint. Therefore, a fast transition to electric vehicles using nickel-rich chemistries is likely to lead to an increase in GHG emissions from nickel production and/or to capture some of the production used in other sectors, mainly stainless steel.

Policies are currently being developed to address this issue. For instance, the new EU battery regulation aims at limiting the carbon footprint of batteries and increasing their recycled content. Unfortunately, such measures might shift, bury, or even increase the problem by incentivizing competition for “green” nickel in certain applications, instead of addressing the underlying issue - a rapidly increasing overall demand for nickel is likely to be met with carbon-intensive production routes. We show that a targeted reduction in the carbon footprint of batteries can potentially be achieved at the expense of other product categories or world regions, which does not help mitigate global emissions. Furthermore, recycled content targets for batteries could encourage the use of stainless-steel scrap to produce recycled nickel for batteries. From a systemic perspective, this is a less efficient use than recycling steel to steel, which could lead to an overall increase in emissions.

This work highlights the potential for modeling global element cycles with demand-driven supply-constrained dynamic material flow analysis models to uncover systemic impacts and risks of problem shifts associated with fast transitions.

This abstract belongs to the proposed special session “Securing raw materials supply for electric vehicles”.

Integrating trade-linked material flow analysis and shock propagation model for assessing global cobalt supply chain risks

Wednesday, 5th July - 11:15: Special Session: Securing raw materials supply for electric vehicles Part 2: Sourcing the battery raw materials of tomorrow - Impact on mineral supply chains (B0.17 KOG)

***Xin Ouyang* [1], *Qiance Liu* [2], *Litao Liu* [1], *Wu Chen* [2], *Gang Liu* [3]**

***1.** Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, **2.** University of Southern Denmark, **3.** College of Urban and Environmental Sciences, Peking University*

As a key critical material for electric mobility transition, cobalt faces increasing supply chain risks in recent years. The pandemic of COVID-19 combined with the Russia-Ukraine conflict exacerbated the already tight global cobalt demand and supply imbalance, which may further hinder our e-mobility and climate ambitions. Despite increasing public and academic attentions, reliable and systematic assessment of cobalt supply chain risks and shock propagation patterns are hitherto not available, particularly not with regional and industry resolutions. In this work, we applied a trade-linked material flow analysis (MFA) to trace cobalt material flows from 1998 to 2019 across 230 world countries and regions. Then, a shock propagation model from complex network theory was combined to reveal shock propagation pathways and patterns both along the life cycle stages and across geographical boundaries, and further to evaluate supply chain risks and robustness based on "systematic fragility" and "exposure rate". We demonstrate that contrasting with the entangled shock propagation processes in single-layer networks, shock diffuses more rapidly along the domestic supply chain than in the international market, because most local shocks would be absorbed via stockpiles and highly connected trade partners. However, shocks originating from a few nodes (countries and life stages), in particular those from mining and secondary production layers, tend to cause catastrophic failures more easily and rapidly. And, these catastrophic failures tend to propagate along similar fixed pathways that are grouped into nine cobalt industry clusters for their highly interconnected and interdependent relationships. Based on the threshold-like behavior of avalanche fraction response to shocks, countries with higher systematic fragility (i.e., Democratic Republic of the Congo, China, the USA, Japan, Belgium, and Finland) and countries with lower systematic fragility but high connectivity (i.e., Kazakhstan, Zimbabwe, Madagascar, and Morocco) are identified as potential risk sources. These results call for system-level actions towards a reliable and resilient global cobalt supply chain and especially highlight the role of international cooperation and technology advancement. Furthermore, traditional risk mitigation strategies like increasing domestic mining and stockpiles are highly influenced by price hikes and may have limited impacts on the downstream and global supply chain. Battery reuse and recycling play a minor but increasingly important role in reducing material extraction and supply risks.

Limited lithium supply is likely to slow down the electrification of the transport sector

Wednesday, 5th July - 11:30: Special Session: Securing raw materials supply for electric vehicles Part 2: Sourcing the battery raw materials of tomorrow - Impact on mineral supply chains (B0.17 KOG)

***Brent McNeil* [1], *Romain Guillaume Billy* [1], *Fernando Aguilar Lopez* [1], *Daniel B. Müller* [2]**

***1.** Norwegian Univ. of Science and Technology, **2.** Norwegian University of Science and Technology*

Most scenarios for climate change mitigation rely on a fast decarbonisation of the transport sector based on a transition to battery electric vehicles (BEV) using lithium-ion batteries (LIBs). Different LIB chemistries exist, all requiring different proportions of critical raw materials which can to some extent be substituted by one another. However, all these chemistries use comparable amounts of

Despite the geologic abundance of lithium, the rate of extraction and processing may fall short of the increasing demand for the electrification of the transport sector. Tensions on lithium supply have already contributed to a price increase of more than 400% in 2021. Continued supply constraints could limit the speed and scale of the electric mobility transition and therefore threaten climate targets.

To analyse potential lithium shortages, we modeled future demand and supply scenarios. Demand scenarios are based on the open-source model MATILDA, which considers several global electrification pathways using parameters such as electrification speed, population, vehicle ownership, size of cars and batteries, battery chemistries, and recycling technologies.

Supply scenarios were defined from an assessment of geologic, economic, environmental, and social constraints related to lithium production. Lithium resources were classified into ten groupings, based on world regions and deposit types. For each grouping, three future supply scenarios were defined: "Probable", "Optimistic", and "Breakthrough", assuming increasing levels of social acceptance for mining and confidence in the development of new extraction technology.

Our results show that lithium supply is unlikely to keep pace with rapidly increasing demand in the next decade. Consequently, this could limit the speed and scale of the transition to electric mobility. This shortfall will be very difficult to mitigate because of the long time required to increase mining capacity. Recycling cannot be scaled quickly enough to close the gap due to the long lifetime of cars. Lithium-free technologies, such as sodium-ion batteries, are unlikely to reach the automotive mass market in the next few years but will be needed to ease lithium demand. On the contrary, new solid-state and lithium-metal batteries require even more lithium than current chemistries. The identified supply gap can only be closed through a reduction in final demand for electric transportation, which means fewer vehicles per capita and/or limitations regarding the size of cars and batteries.

In the long term, the size of the supply gap is more uncertain, and shortages can be avoided under certain conditions. Deep societal changes, close-to-perfect recycling, and a diversity of battery technologies are required to limit demand, while considerable efforts to increase raw material production will be needed to meet Net Zero scenarios.

This abstract belongs to the proposed special session "Securing raw materials supply for electric vehicles".

Is lithium from geothermal brines the sustainable solution for Europe?

Wednesday, 5th July - 11:45: Special Session: Securing raw materials supply for electric vehicles Part 2: Sourcing the battery raw materials of tomorrow - Impact on mineral supply chains (B0.17 KOG)

Vanessa Schenker [1], ***Christopher Oberschelp*** [1], ***Peter Bayer*** [2], ***Stephan Pfister*** [1], ***Stefanie Hellweg*** [1]

1. *Institute of Environmental Engineering, ETH Zurich,* ***2.*** *Martin-Luther-Universität Halle-Wittenberg*

Lithium is classified as a critical raw material in Europe due to its importance for lithium-ion batteries and related supply risks. Simultaneously, the battery regulation of the European Union intends to ensure the reporting and limitation of greenhouse gas emissions of battery production as well as of involved supply chains. The novel technology of co-producing lithium and geothermal power in Europe (e.g., in the Upper Rhine Graben in Germany and France) is under development to mitigate European supply risks. Still, it is unclear under which conditions this technology could have lower environmental impacts compared to the global average of lithium production. Data availability and quality are still poor, making the assessment of life cycle impacts difficult.

To address this knowledge gap, we have developed a parametrized and modularized tool to model life cycle inventories for lithium extraction from geothermal brines at specific sites. For this, we have used data from an upcoming German plant as a starting point. These data were adapted by varying technical and environmental parameters to create a range of life cycle inventories representing potential future changes. These inventories were utilized to quantify environmental impacts (i.e., climate change impacts based on IPCC (2021)) of 1 kg lithium carbonate with battery grade. Ecoinvent v3.9.1 was chosen as an inventory data source for the background system.

The results highlight the importance of specific parameters (e.g., initial lithium concentration) regarding the required inputs and associated environmental impacts per kg of product. For example, the electricity demand to produce lithium carbonate is highly dependent on the lithium concentration in geothermal brines, while the heat demand stays rather unaffected. This has strong implications for lithium extraction from geothermal brines. With regard to future production, one particular concern is an unstable and potentially decreasing lithium concentration over time due to the re-circulation of the brine into the ground. The thermal conditions may generate faster than the lithium concentration, which finally can only be overcome by drilling new deep boreholes and thus expanding the reservoir. These investments would then cause additional environmental impacts which need to be allocated between the energy provision and lithium extraction. Finally, the comparison with conventional technologies reveals how co-produced lithium from geothermal systems could be extracted in a sustainable manner.

Participatory life cycle assessment of direct lithium extraction from geothermal brines

Wednesday, 5th July - 12:00: Special Session: Securing raw materials supply for electric vehicles Part 2: Sourcing the battery raw materials of tomorrow - Impact on mineral supply chains (B0.17 KOG)

Margaret Slattery [1], ***Alissa Kendall*** [1], ***William Evans*** [2], ***Nadiyah Helal*** [1], ***Kristi Dayemo*** [2]

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The Just Transition framework calls for climate strategies that repair inequality and avoid environmental harm. From a life cycle perspective, this requires developing sustainable supply chains for clean energy minerals such as lithium, which is needed to make electric vehicles and stationary storage batteries. Tools from industrial ecology, such as life cycle assessment (LCA), are well-suited to understand environmental impacts more holistically. However, traditional industrial ecology has gaps related to the lack of spatial resolution and erasure of impacted populations, which limit the field's capacity to evaluate climate strategies within a just transition framework. One promising solution is participatory LCA, which integrates the perspectives of people who stand to be affected by or influence the system being studied. Here, we conduct a participatory LCA of direct lithium extraction (DLE) from geothermal brines in Imperial, California ("Lithium Valley"). DLE separates lithium from brine through chemical processing rather than relying on the slower process of natural evaporation. DLE from geothermal brines is generally considered a sustainable alternative to evaporation or hard-rock mining; however, the technology is still developing.

We use content analysis of public meeting transcripts and survey data to determine the most relevant impacts for stakeholders and focus on the corresponding LCA impact categories in our analysis. We then analyze the impact of producing one ton of lithium carbonate (Li2CO3) and lithium hydroxide (LiOH), using patent data as a basis for the inventory of material and energy flows. The results of the LCA are compared with status quo production methods and situated within the local context, with discussion that focuses on how they respond to the concerns or expectations of local stakeholders. To make the information more useful to local stakeholders, the drivers behind impacts are clearly explained, and the significance of the impacts is compared to other activities in the area (for example, agriculture).

To date, there has only been one non-industry LCA of DLE. This study will thus address multiple gaps by advancing the field of participatory LCA and providing more data about the impacts of DLE. More broadly, this research provides an example of incorporating local perspectives and knowledge into environmental impact assessments of products that are generally evaluated based on global impacts. To date, no participatory LCAs have been conducted for clean energy materials, although the methodology could be essential to informing climate strategies consistent with the just transition framework.

Special Session: Socio-Economic Transitions and Life-Cycle Governance

Socio-Economic Drivers of Material Efficiency: Evidence from a Panel of Countries

Wednesday, 5th July - 11:00: Special Session: Socio-Economic Transitions and Life-Cycle Governance (A1.44 KOG)

Xiao Li [1]***, Xuezhao Chen*** [1]***, Haijia Shi*** [2]***, Ruichang Mao*** [3]***, Junming Zhu*** [3]

__1.__ Xi'an Jiaotong University, __2.__ Research Center of Circular Economy and Cleaner Production, South China Institute of Environmental Sciences, Ministry of Ecology and Environment, __3.__ Tsinghua University

Material efficiency strategies are seen as a promising solution to achieve sustainable resource utilization and to minimize environmental impact while fostering economic growth. This study analyzes the impact of socio-economic drivers on material efficiencies across countries and identifies the key differences among them. Using data from 1970 to 2016, the study defines material efficiency as the ratio of economic output to the use of materials and employs regression analysis to examine the average and heterogeneous effects of various socio-economic factors, such as GDP, population, trade openness, natural resource endowments, technological progress, and human capital. The findings reveal that only GDP and technological progress have a significant, positive impact on material efficiency when considering the average effect across all countries. However, the study finds significant cross-country differences in the impact of socio-economic factors on material efficiency. For example, the impact of GDP and population is stronger in developing countries, while technological progress and urbanization have the opposite effect. Similarly, the impact of socio-economic factors on material efficiency is different between high and low trade openness countries, as well as countries with high and low natural resource endowments. The study highlights the importance of balancing the positive effects of socio-economic drivers with potential negative impacts on material efficiency, and suggests that improving human capital is a way to address the trade-off between population growth and its negative impact on material efficiency. The results of this study have important implications for industrial ecology and can inform policy makers, business leaders, and researchers in formulating strategies and initiatives to enhance material efficiency and promote industrial sustainability.

Note: This abstract contributes to the proposed special session "Socio-Economic Transitions and Resource Implications"

Evaluating the Supply Risk of Bulk Commodities: Based on the Perspective of Physical Trade

Wednesday, 5th July - 11:15: Special Session: Socio-Economic Transitions and Life-Cycle Governance (A1.44 KOG)

***Jianlimin Wei* [1], *Wei-Qiang Chen* [1]**

1. *Institute of urban environment, CAS*

Bulk commodities including agricultural products, metals, and energy fuels are fundamental resources sustaining modern society, and their supply risks resulting from international trade have been paid great attention by scientists and policymakers. However, although many studies have evaluated the supply risks of specific bulk commodities in certain countries and areas, few have compared the supply risk of various commodities of countries concurrently, which is vital in understanding the interdependency and competition for raw materials among the countries.

Based on the modified Hirschman-Herfindahl Index (HHI) which considers the supply diversity, supply ability, and willingness of exporting countries, this study assesses the supply risks of 21 typical bulk commodities (including agricultural products, metals, and fossil energy materials) of the top three net importers (China, Japan, and the USA) for the decades spanning 1992–2019.

Key preliminary findings include the following: (1) as the largest net importer, China's supply risk increased for 18 of 21 bulk commodities during the past 28 years, compared with 14 for Japan and 8 for the USA; (2) Japan and China had the greatest supply risk in agricultural products, while the USA in energy materials. This analysis provides dynamic insight into the supply risk of bulk commodities of the three largest economies, China, Japan, and the USA, which can inform international competition potential and interdependency.

Does a reduction in working time matter for the environment? The case of Japan

Wednesday, 5th July - 11:30: Special Session: Socio-Economic Transitions and Life-Cycle Governance (A1.44 KOG)

Yosuke Shigetomi [1], ***Andrew Chapman*** [2]

1. Nagasaki University, 2. Kyushu University

A shrinking labor force is an important aspect of sustaining the economy. Most economically developed nations are facing the risk of a reduction in labor forces due to an aging and lower birth late trend that decreases the working population (i.e., the 15-64 year-old-population). If a decline in gross production outputs is undesirable, on the one hand, labor productivity through considering "how to work" must be improved to complement the lack of a working population. On the other hand, however, if a decline in production is accepted, environmental pressures would be alleviated due to a drop in associated consumption activities.

This study sheds light on Japan as a case study, because it is a nation with one of the highest levels of a decreasing working population, by 40% in 2065 compared to 2020 due to an aggressively aging society with a reduced birth rate. Besides, the labor productivity of Japan is ranked 21st among 34 nations belonging to the Organisation for Economic Co-operation and Development and has been decreasing in recent years. In particular, long working hours have been an issue in Japan, with a well-known Japanese word *Karoshi*, which means death by overwork. Therefore, a gain in labor productivity that can result in avoiding long working hours would be crucial for sustaining Japanese society regarding the economic, social, and environmental aspects.

Against this backdrop, the research question of this study is as follows: How could addressing overwork issues reduce greenhouse gases (GHG) emissions in Japan? Then, what will be the influence on the gross domestic product (GDP)? To answer these questions, we demonstrate the environmental input-output analysis combined with national labor statistics. Through the analysis, policy implications for establishing sound working conditions and climate change mitigation are argued.

The methodology constitutes a time-series input-output table with supplemental growth accounting (JIP-IO) to measure the impact of reducing working time on GDP and GHG emissions. The growth accounting allows us to predict each impact of labor inputs, capital stock inputs, and other factors (i.e., total factor productivity) on changes in the total output and the value added in each sector on JIP-IO. This study decomposed the labor inputs into the working population and the annual working hours by industry sector and estimates the impact of changes in annual working hours regarding a reduction in excessive working hours and expected working hours to be examined in a national survey taken during last year.

The preliminary result shows that the GDP loss and the associated GHG emissions reduction in Japan would account for 5.2% and 6.8% respectively, when the annual working hours were reduced in line with the amount of excessive working hours by industry. The GDP loss can be translated to a per-capita GDP loss of 0.20 million JPY/year in the 2011 real price (the annual per-capita GDP is about 4.2 million JPY/year in the recent five years). At the conference, we will elaborate on the detailed methodology and further discussions based on the results for balancing working hours, economic growth (GDP), and GHG mitigation.

Restoring the Incentives for Eco-design in Extended Producer Responsibility: The Challenges for Eco-modulation

Wednesday, 5th July - 11:45: Special Session: Socio-Economic Transitions and Life-Cycle Governance (A1.44 KOG)

Reid Lifset [1], ***Harri Kalimo*** [2], ***Antti Jukka*** [3], ***Petrus Kautto*** [4], ***Mirella Miettinen*** [3]

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Extended producer responsibility (EPR) is an environmental policy strategy that makes producers responsible for the waste management of their products and packages. A key goal of EPR is to incentivize producers to (re)design their products and packages to improve their environmental performance, especially at end of life. EPR facilitates the closing of loops and, as such, is considered by many to be a key policy strategy for industrial ecology and the circular economy.

However, because of the way in which the financial structure of EPR has evolved, those incentives have largely been muted or undetectable. Eco-modulation has emerged as an additional component in EPR to restore the missing incentives for eco-design. Eco-modulation operates through changes in the fees that producers pay to meet their EPR obligations. Eco-modulation includes both increased differentiation of types of products and associated fees, and additional bonuses and penalties—environmentally targeted discounts and surcharges on the fees that each producer pays.

Eco-modulation faces challenges if it is to restore the incentives for eco-design. These include weak linkages to environmental outcomes, fees that may be too low to induce changes in materials or design, lack of adequate data and *ex post* policy evaluation, and implementation that differs across jurisdictions. Opportunities to address these challenges include use of life cycle assessment (LCA) to inform eco-modulation, increased eco-modulation fees, strategies to increase harmonization of eco-modulation implementation, mandated provision of data, and policy evaluation tools that establish the efficacy of different eco-modulation schemes. Considering the scope of the challenges and the complexity of establishing eco-modulation programs, we suggest treating eco-modulation at this stage as an experiment on promoting eco-design.

Nudging Household Sustainable Behavior: The Role of Life Cycle Impact and Social Norms

Wednesday, 5th July - 12:00: Special Session: Socio-Economic Transitions and Life-Cycle Governance (A1.44 KOG)

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Household consumption induces considerable environmental impact. Changing household consumption behavior receives more and more attention both from researchers and practitioners. With recent development in behavioral economics, nudging is now considered as a promising tool for inducing behavioral changes. With designed information or decision environment, individuals and groups could be nudged to make socially desired choices.

Social norm-based nudges have been proved effective in encouraging common sustainable behaviors like water conservation and energy saving. Their effects for less publicly known sustainable behaviors, however, remain to be explored, with both positive and insignificant empirical evidences. Life cycle analysis information could serve as a new tool for nudging sustainable behaviors, as it takes account of the impact beyond the consumption process itself, which may elicit externality-related thinking of consumers.

This study explores the effectiveness of life cycle impact and social norm information to nudge household sustainable behaviors—a series of sustainable laundry behaviors specifically, which are less regulated and less covered by public discussions, providing a relatively clean research setting. The life cycle water and electricity consumption of laundry behavior are displayed respectively in the form of per year per capita, per year for a country, and per year for a country compared with the water and electricity consumption of a reference province. Social norm nudges are displayed respectively as injunctive social norm (this is the right thing to do) and descriptive social norm (this is what other people commonly do). In addition, the effectiveness of life cycle impact and social norm information combined is explored.

The causal relationship between the nudges and sustainable behavior is identified using randomized controlled trials (RCTs) and ordered logistic regressions. The RCTs took place online from April to May 2021 with 2677 respondents from a nationally representative sample in China. Gender, age, profession, education, income, place of residency, sustainable behavior knowledge, and environmental awareness are controlled as covariates in the regressions.

The analysis shows that low-cost sustainable laundry behaviors like adjusting the working temperature of washing machines are more likely to be nudged, in contrast to more complicated behaviors like purchasing concentrated detergent and decreasing washing frequency. Life cycle impact information is effective only when displayed with a reference to compare. Descriptive social norm information is effective and shows extra effect when combined with life cycle information, yet injunctive social norm information is ineffective and could partly offset the effect from life cycle information.

This study proposed life cycle information as a new tool for nudging sustainable behaviors, tested its effectiveness using RCTs, and found that it could promote sustainable behaviors when displayed with a reference rather than as raw data. This research also contributes to the discussion of whether social norm nudges are effective in encouraging less common sustainable behaviors. The RCTs showed that descriptive social norms, considered as softer nudges, are more likely to be effective in encouraging less familiar sustainable behaviors. Combined with life cycle information, descriptive social norms had extra effect, while injunctive norm message could offset the effect from life cycle information. Governments and institutions could make use of life cycle data and descriptive social norms to promote new ways of sustainable consumption, but should be cautious about the use of injunctive norms, which may backfire.

Beyond market failure: a rationale for life cycle policymaking

Wednesday, 5th July - 12:15: Special Session: Socio-Economic Transitions and Life-Cycle Governance (A1.44 KOG)

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Environmental policy analysis is traditionally informed by microeconomic theory and the market failure framework. However, this is not the only approach to environmental policy. Increasingly, governments apply life cycle thinking, which focuses on product life cycles (or value chains) instead of markets. Life cycle policymaking is rooted in a view of goods and services as product systems: the sum of processes from raw material extraction to end-of-life disposal that contributes towards the fulfilment of a specific demand.

Welfare economists have formulated a coherent rationale for intervention, which is widely used by governments and even codified in the legislative frameworks of some countries (including the US), but policymakers lack a comparable rationale for intervention from a life cycle perspective. In this study, we identify an analogous rationale for life cycle policymaking. The broader aim of the study is to equip policymakers with an analytical understanding of when and how to intervene based on life cycle thinking and evidence.

In a nutshell, the market framework postulates that under ideal conditions, the unobstructed operation of the market yields the best possible allocation of resources and thus the highest welfare. Market failures are deviations from the ideal functioning of the market, which lead to lower welfare. Life cycle policymaking is based on an altogether different starting point. It does not focus on markets, supply, demand, and prices. Instead, its starting points are product systems and material life cycles.

In our tentative definition, life cycle policymaking aims to intervene in one stage of the product life cycle to prevent or reduce harmful effects in another stage of the life cycle, often across space and time, based on an understanding of the systemic interactions across the life cycle. This type of policymaking aims to exploit leverage points in the product system, such as the choices of product designers, based on an understanding of the relationships between the flows of materials and energy.

We explain the rationale for intervention through life cycle policies with a focus on systemic leverage points, the multiple challenges of regulating across jurisdictional boundaries, and the role of hard life cycle evidence. To illustrate the application of the framework, we reflect on historical policy decisions through the lens of the new rationale. Our study provides a first step towards a coherent approach for deriving policy interventions from life cycle thinking and evidence, which can support a multidisciplinary approach to environmental policymaking.

LCA methods 3

Development of an effect factor for marine plastics' impact on cultural ecosystem service

Wednesday, 5th July - 11:00: LCA methods 3 (B0.25 KOG)

Fei Song [1] ***, Francesca Verones*** [1] ***, Martin Dorber*** [1] ***, Johan Pettersen*** [1]

1. *Norwegian Univ. of Science and Technology*

Oceans are key for achieving a more sustainable future. Marine ecosystems provide abundant ecosystem services, such as provisioning services from seafood or tabby concrete, cultural services from recreation or education, or regulating services from climate regulating to coastal protection. It has been estimated that the total worth of annual global marine ecosystem service is 33 trillion dollars. Among all marine ecosystem services, the cultural services, which include aesthetics, recreation, education, and spiritual values, are among the most distinctly perceived marine ecosystem services for the general public. In 2021, the market of global coastal and maritime tourism was estimated at 2.9 trillion dollars, and it is anticipated to have an annual growth rate of 5.7% from 2022 to 2030. However, marine cultural services are also confronted with more and more stressors emerging from human activities, such as climate change, overfishing, invasive species, or marine plastic debris. Plastics debris has become one of the most serious problems affecting marine ecosystems, including their cultural services, leading to weakened tourist attractiveness, impaired cognitive value, and reduced aesthetics value.

Life cycle assessment (LCA) is one of the most used tools to quantify environmental impacts from human activities. However, LCA currently does not consider marine cultural ecosystem services. This shortcoming is mainly due to the traditional focus in LCA on terrestrial and freshwater ecosystems, and that cultural ecosystem services are under-researched compared to other marine ecosystem services such as provisioning services.

We aim to contribute to the construction of new characterization factor by developing an effect factor for macroplastics´ impact on recreation value loss of marine cultural services through willingness to pay (WTP). In our research, high-dimensional linear regression of independent variables including income, education, and exposure to marine plastic of coastal countries were chosen. Our outcome offers the first regionalized effect factor accounting for macroplastics debris´ damage to marine cultural ecosystem service.

Using Consumer Archetypes to Model the Use Phase of LCA with a Case Study on Urban vs. Rural E-Commerce

Wednesday, 5th July - 11:15: LCA methods 3 (B0.25 KOG)

Shelie Miller [1]***, Luyi Huang*** [1]

1. *University of Michigan*

Consumer behavior can have a major impact on the environmental impact of products. Use phase data that involve consumption patterns often rely on average data, using distributions or scenarios to explore the sensitivity of use phase assumptions. There are often correlations within probability density functions associated with use-phase parameters that are usually not explored explicitly in LCA. While many LCA case studies will specifically link parameters associated with consumer behavior with differences in environmental impact results, these parameters are usually considered individually rather than as a package of user characteristics. This presentation advocates constructing scenarios around specific consumer archetypes that contain a suite of related parameters to more explicitly show how LCA results can be influenced by different kinds of adopters. The case study of adoption of grocery e-commerce by urban and rural customers will be explored to show the importance of considering different kinds of potential adopters in LCA. In addition to very different last-mile scenarios, consumers in urban and rural areas have very different purchasing habits and behaviors, particularly with respect to frequency of shopping trips, number of items purchased during a shopping trip, and 'trip-chaining,' or combining multiple activities in one trip. We assess how direct and indirect factors impact the environmental impacts of e-commerce of grocery delivery compared to a traditional brick-and-mortar grocery store, for rural and urban customers. Specifically, consumer archetypes or urban and rural consumers are constructed for differences in last-mile distance and transportation mode, fulfillment via distribution centers or existing retail, consumer purchasing behavior in the form of shopping frequency, trip-chaining, and basket size, changes in food waste throughout the supply chain, and auxiliary household cold storage. This study will demonstrate how construction of specific consumer archetypes can provide very different insights when compared parameter distributions of an entire population as well as scenario analysis of specific individual parameters.

Towards a biodiversity-inclusive strategy for the extraction of raw materials

Wednesday, 5th July - 11:30: LCA methods 3 (B0.25 KOG)

Valerio Barbarossa [1]***, Alexandra Marques*** [2]***, Aafke Schipper*** [2]***, Mélanie Douziech*** [3]

1. *Leiden University,* ***2.*** *PBL Netherlands Environmental Assessment Agency,,* ***3.*** *MINES Paris*

Mining is an integral part of the global economy, providing the minerals necessary for construction, energy production, agriculture, and manufacturing. Despite its crucial role, mining activities can have significant impacts on biodiversity, as up to 37% of the global land area might be affected by mining. This is a growing concern, as to hit net zero globally by 2050, we need six times more mineral inputs than today already by 2040. In this study, we aim to quantitatively assess the impacts of mining activities on biodiversity and provide recommendations for incorporating them into sustainability assessment tools, such as Life Cycle Assessment (LCA). Our meta-analytical approach analyzed data from 257 globally distributed mining sites and over 1,500 species across the terrestrial, freshwater, and marine realms, including various mine types (e.g., open pit, underground) and materials (e.g., metals, coal, sand). Our findings reveal that species richness declined significantly due to mining operations for all realms, with notable differences across realms. Changes in abundance were dependent on the taxonomic group, with freshwater species showing the largest declines. We also found that impacts varied depending on the materials being mined. This study provides the first comprehensive quantification of the impacts of mining on biodiversity and highlights the importance of considering biodiversity in the development of characterization factors that can support sustainable development. Our results can help inform the development of sustainability assessment tools, such as LCA, by incorporating the effects of mining activities on biodiversity and supporting the development of biodiversity-inclusive strategies. The findings of this study are critical in addressing the ongoing biodiversity crisis and ensuring a more sustainable future.

Dynamic Life Cycle Analysis for Innovative Wood Products and Marginal Land Afforestation and Reforestation

Wednesday, 5th July - 11:45: LCA methods 3 (B0.25 KOG)

***Bingquan Zhang* [1], *Kai Lan* [1], *Thomas B. Harris* [2], *Mark S. Ashton* [2], *Yuan Yao* [1]**

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Afforestation and reforestation (AR) is a nature-based solution to increase carbon stock and mitigate climate change. Un-used or degraded agricultural lands and non-stocked forest, generally called "marginal land", are good options for AR. Using non-vegetated marginal land can reduce social and economic competition with other land uses and avoid land use change emissions due to their almost zero aboveground carbon stock. There are different AR strategies, such as protection AR for ecological system conservation and commercial AR that supplies timber and raw materials for industrial products. The greenhouse gas (GHG) mitigation efficacy of different AR strategies is still under debate. Previous life cycle assessment (LCA) studies compared protection and commercial AR focusing on traditional wood products (e.g. lumber)[1] or compared different product combinations in existing forests [2]. Innovative wood products such as Cross-laminated timber (CLT) [3] and biochar [4], have been evaluated by previous LCA studies at a process- or product-level. However, few have considered the impacts of forest carbon dynamics and AR strategies at different spatial and temporal scales.

This study fills the research gaps by presenting a dynamic, multi-scale LCA that links process-scale LCA for innovative wood products with regional-scale modeling of forest ecosystems. The dynamic LCA estimates 100-year GHG mitigation potential of protection and commercial AR with different planting densities and thinning practices on marginal land in the southeastern US. Protection AR without harvesting is the baseline. Two commercial scenarios are included. One is traditional AR for lumber production without residue removal, the other is innovative AR for CLT production and residue removal for biochar production. Our results indicate that across 100 years, innovative AR has higher GHG mitigation potential (3.73–4.15 Gt CO_2e) than protection AR (3.35–3.69 Gt CO_2e) and traditional commercial AR (3.17–3.51 Gt $CO_{2\text{-eq}}$). However, protection AR is likely to achieve higher GHG mitigation in a shorter timeframe (≤50 years). Forest plantation management, such as high-density plantations with thinning, has better GHG mitigation efficacy than low-density plantations. Our spatial analysis identified uneven spatial distributions of carbon stock increase of various carbon pools and this talk will present regions with high priorities for innovative commercial AR projects on marginal land.

The results of this study highlight the importance of strategically synergizing different nature-based solutions, as well as the role of innovative commercial AR in mitigating climate change, establishing long-term carbon sinks, and providing timber and raw materials for wood products. This study also demonstrates the powerful use of the dynamic, multi-scale LCA framework as a transdisciplinary research tool that sits at the intersection of industrial ecology and forest ecology.

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Life Cycle Assessment for Nature-positive and Circularity Outcomes

Wednesday, 5th July - 12:00: LCA methods 3 (B0.25 KOG)

***Delwyn Jones* [1], *Mathilde Vlieg* [2], *Shloka Ashar* [1]**

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The United Nations Nature Positive (N+) Program provides a global impetus for environmental science and industrial ecology to consider gain versus loss in climate and biodiversity security. Program goals stress that few decades are left to resolve accelerating climate and extinction crises amidst market turmoil in all personal to global

activity. But literature reviews show, that despite being marketed under positive banners, most so-called positive assessment tools are negatively-skewed on less to zero damage.

So, to manage N+ outcomes, humanity must sight, define and measure benefits and gains of action seeking net-positive outcomes. Transitioning to a nature-positive world demands extending scientific sightlines beyond damages and zero loss to benefits, gains and regeneration. The aim is to clarify concepts then review Life Cycle Assessment (LCA) methods and real-world third-party-certified case studies to illustrate core N+ numeracy and literacy for industrial ecology and the circular economy.

The literature shows that accelerating anthropogenic climate change and biodiversity loss earns global responses. Prevailing reactions, however, include bad news, greenwash, disinformation and community indecision. The general populace is reportedly confused, and tuning out bad news so inaction ensues. Youth activism is driven by learning about their inheriting mass extinctions and climatic extremes. This compounds worsening youth mental health after the CoVID pandemic.

The political science quandary is that despite climate viability and biodiversity losses, current responses are hindered by justifiably net-negative literacy and numeracy. Current quantification of diminishing ecological returns lacks the reach to effectively recognise and measure ecological benefits, gains and returns on investment (ROI). So to create change and solutions N+ and net-positive numeracy and literacy are vital

To guide N+ development, plans and policy, globally, initiatives need messages, measures and metrics integrating benefit and gain. But conventional science lacks key codewords and accounting for net-positive climate and biodiversity outcomes, to access action and restore capacity to preindustrial ecological security. That is why this work applies a Life Cycle Assessment of Benefit (LCBA) and Impact (LCIA) indicator framework to model net-loss versus net-gain in climate security, supply viability and human wellness.

Cradle to grave case studies include a commercial kitchen diverter that separates fat, oil and grease feedstock to be recovered to make biodiesel. Overall results show reduced damages, five benefits and a net gain compared to no diversion. Other recycled and renewable product, building and infrastructure case studies show net-positive climate and biodiversity security. The work shows how LCA can model net-positive climate, wellness, biodiversity and supply security.

By unwittingly excluding beneficial gain LCA suffers a negative bias that disempowers communication and creates barriers for quantification of regenerative initiatives. Benefit- supplemented-LCA offers community, government and business new scientific methods for modelling gain and accelerating system security. Reporting positive gains well-beyond negative and zero loss, enables truer market assessments. The capacity to report positive metrics and ROI also reduces needs for greenwashing and bad news. Such extended N+ reach offers hope to inspire wider public action that is essential considering the huge gains needed to restore natural planetary control systems. The authors, therefore, recommend extending the reach and capacity of industrial ecology to include net-positive concepts, math and messaging.

Assessing the greenhouse gas tradeoffs of alternative agrivoltaics technologies in the U.S. Midwest: connecting biophysical input-output and prospective life-cycle assessment

Wednesday, 5th July - 12:15: LCA methods 3 (B0.25 KOG)

Nathaniel Springer [1], ***Rylie Pelton*** [1]

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Installation of large-scale solar projects has increased dramatically in recent years due to cost reductions, long-term demand projections, and policy incentives. In the Midwest U.S., such installations predominantly replace agricultural land, which regional critics bemoan as culturally unsuitable. Simultaneously, land management underneath panels is commonly gravel or turfgrass, which provides negligible benefits beyond the clean energy of solar production.

One alternative strategy is agrivoltaics, which combines solar and agricultural production practices. Numerous options are beginning to be tested and implemented – including grazing livestock (Kochendoerfer et al. 2022; Pandey et al. 2022), growing biofuel (Leirpoll et al. 2021), or planting natural habitat (Walston et al. 2018) – each with its unique economic, social, and environmental costs and benefits.

Here we present an approach that organizes process-based life-cycle assessment (LCA) of the greenhouse gas impacts of these prospective agrivoltaic practices using biophysical input-output tables. Such a technique makes it easier to expand the boundaries of the bottom-up LCA data to include the technology mix of the energy sector and future decarbonization assumptions in prospective scenarios. It also enables, with addition of prices, a straightforward way to calculate monetary costs and economic returns of these scenarios in the price dual of the biophysical input-output table. We illustrate this approach using an example for the U.S. state of Minnesota at the county scale.

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EEIOA cases 3

Research on the impact of border carbon adjustments on climate justice in international trade

Wednesday, 5th July - 11:00: EEIOA cases 3 (B0.31 KOG)

Yanan Ren [1]***, Jinping Tian*** [1]***, Lvjun Chen*** [1]

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Climate justice is crucial for "Goal 10: Reduced Inequalities" and "Goal 13: Climate Action" of the UN Sustainable Development Goals. As significant climate actions entailing levies on the imports of carbon-intensive goods, border carbon adjustments (BCAs) are bound to trigger both economic and carbon consequences and thus affect climate justice in international trade. Therefore, this research focuses on BCAs' impact on climate justice in trade, taking the EU Carbon Border Adjustment Mechanism (CBAM) as an example.

The pollution-to-wealth or emission-to-wealth ratio is widely used to represent ecologically unequal exchange. To quantitatively evaluate the impact of BCAs on climate justice, we defined the "carbon emission-to-value added" ratio hidden in trades as the Climate Inequality (CI) index and measured the variation proportions of the CI index caused by entailing levies on imports. CBAM's five regulated sectors—cement, aluminum, fertilizers, iron and steel, and electricity—are considered. First, we quantified CBAM costs by sector and economy considering four parameters—trade volume, embedded emission intensity in trade, carbon price, and free allowance ratio. Export volumes to the EU were compiled based on 2019 trade statistics from the BACI database. Data on embedded emission intensity in trade were retrieved from multiple sources like life cycle inventory and input-output databases. We adopted a carbon price of 100 euros/tonne and a free allowance ratio of 0% to explore the extreme condition. Second, we employed the Embodied Emission in Bilateral Trade (EEBT) model and the Exiobase database to calculate the CI index by measuring the increases in domestic economic profits and carbon emissions induced by trades. Final, combining the previous results, we quantified the variation proportions of the CI indices caused by CBAM. We also estimated the uncertainties arising from national/regional exports to the EU and embedded carbon intensities.

The total CBAM cost will be 3.2 billion euros or 5.5% of exports to the EU and be dispersed across economies and sectors. The region burdening the most CBAM cost will be the rest of Europe (WWE) (1.0 billion euros), followed by Russia (0.4 billion euros), Turkey (0.4 billion euros), China (0.3 billion euros), etc. The total CBAM levies of the regulated sectors will be 2.1 billion euros (Iron and Steel), 0.6 billion euros (Fertilizer), 0.3 billion euros (Aluminum), 0.2 billion euros (Cement), and 0.3 million euros (Electricity), respectively. Cement will be the highest affected sector, whose CBAM cost will account for 80.5% of the trade volume, followed by Fertilizer (11.7%), Iron and steel (6.7%), Aluminum (1.8%), and Electricity (0.01%). Most developing economies' CI indices were greater than 1.0 in 2019, exampled by WWE (2.8), Indonesia (2.0), and South Africa (1.9), which means they assumed heavier emission responsibilities than the economic benefits gained from exports. On the contrary, most developed economies' CI indices were less than 1.0, exampled by the US (0.4), the UK (0.4), and the EU (0.5). The maximum and minimum variation proportions of the national/regional CI indices will be 3.2% (WWE) and 0.4% (USA), respectively. Most developing economies' CI indices will increase by high proportions due to low value-added intensities and high emission intensities of their exports. In contrast, industrialized economies will see little changes in their CI indices. This study supplemented a climate justice perspective for discussion about the impact of BCAs among academia, industry, and policymakers and shed light on future policy improvements.

Opportunities and limitations of increasing the geographical resolutions in input-output models

Wednesday, 5th July - 11:15: EEIOA cases 3 (B0.31 KOG)

***Anniek Kortleve* [1], *José Mogollón* [1], *Paul Behrens* [1]**

1. *Leiden University, CML*

Increasing the geographical resolution of environmentally-extended input-output models would provide policy makers with specific insight into local environmental issues. As local data are often limited, and their collection requires expensive and time-consuming surveys, non-survey approaches have been developed to produce subnational tables from national tables algorithmically. These regionalisation approaches can facilitate the exploration of local impacts, and local-international trade patterns and help reveal local opportunities that may be masked in national input-output data. However, regionalization also comes with trade-offs regarding data uncertainty.
Here, we would like to highlight both sides with a case study on EU flows by applying a novel-regionalization approach. The novelty of this algorithm lies in the traceability of its calculations, that it does not rely on supplemental balancing procedures (e.g., RAS), only requires readily available additional proxy data, and is applicable to any input-output model. The regionalized countries remain nested in its multi-regional framework and so maintain their connections to the environmental extensions.
The subnational analyses revealed domestic and international trade patterns and opportunities and shows that subnational differences can be as large national ones. Although the method addresses previous issues of data dependency, global connection, and disaggregation of all input-output elements, other issues remain, of which the issues related to concordance between proxy and input-output data, consistency with the national account, and balancing by value-added will be further discussed to provoke further discussion on its use for environmental and socio-economic footprint analyses.

Why carbon emissions mismatch with economic gains? An explanation from value chain perspectivee

Wednesday, 5th July - 11:30: EEIOA cases 3 (B0.31 KOG)

Ailin Kang [1], ***Yiling Xiong*** [1], ***Xin Tian*** [1], ***Ludi Liu*** [1]

1. *Beijing Normal University*

As carbon mitigation is a common issue faced by countries and regions, seeking for fair strategies to curb emission across multiple regions become a challenge for the globe. Previous efforts have been well made to identify the imbalanced profile of economic gain and carbon emission, whilst the underlying mechanism of mismatched allocation on sophisticate production network remains largely unknown. This study traced imbalanced flows of value added and carbon emission along China's domestic value chain during 2007–2017, and explained the imbalance from perspectives of production division of labor. Northern inland regions were at upstream position in domestic value chain that dominated by supplying resource and energy related intermediate products, presenting 1.8~6.5 times carbon intensity than other regions. Meanwhile, coastal regions at the downstream occupied more manufacturing and services, and final products supplies with highly value added, enlarging the inequalities between the coastal and inland regions. It highlights the importance to explore mechanism to relieve regional inequality of economic benefits and emission reduction responsibility from the perspective of value chain.

Global Carbon and Material Footprints of Machinery Capital

Wednesday, 5th July - 11:45: EEIOA cases 3 (B0.31 KOG)

Meng Jiang [1], Ranran Wang [2], Richard Wood [3], Edgar Hertwich [1]

1. Norwegian Univ. of Science and Technology, 2. Institute of Environmental Sciences (CML) - Universiteit Leiden, 3. NTNU

Manufactured capital, including machinery, equipment, buildings, and other durable goods, provides shelter, products, and services essential for human well-being. The manufacturing of machinery and Equipment (M&E) is responsible for 8% of global emissions and 35% of the carbon footprint of materials, which is second only to the construction sector (Hertwich 2021). Current climate mitigation studies show our society will require more M&E to achieve climate goals, including wind turbines, solar panels, batteries, smart grids, and digital facilities, all necessary to transition to a clean energy system and a circular economy production system (Lee, Bazilian et al. 2020).

M&E are capital assets, accumulated in the form of material stocks which define the production system. Once built, M&E lock in the environmental consequences for decades of their lifetime (Seto, Davis et al. 2016, Södersten, Wood et al. 2018, Södersten, Wood et al. 2018, Tong, Zhang et al. 2019, Berrill, Miller et al. 2020). Further, the capital is also a resource repository, which is the most important destination for carbon-intensive materials such as aluminum, copper, precious metals, and other non-ferrous metals (Pauliuk and Müller 2014). After retirement, promising opportunities for a circular economy will occur, including remanufacturing, reuse, and recycling.

However, too few studies exist to evaluate the environmental impacts of producing M&E and the environmental footprint embodied in M&E cohorts over years. Here we develop a approach by integrating environmentally extended input-output analysis (EEIOA) and dynamic-material flow analysis (d-MFA) to shed the light on the M&E development over five decades across regions. We analyse the greenhouse gas (GHG) emissions, materials footprint (MF) and metal requirements of producing machinery. We further evaluate the environmental footprint embodied in machinery stocks and their relation to economic growth and saturation state.

We show that machinery is the second largest driver of carbon emissions and material footprint in capital formation, just after buildings. In certain areas, demand for metal driven by machinery exceed that of buildings. In terms of environmental flows driven by machinery production, developing regions, especially China, are growing rapidly. China has overtaken Europe on the per capita basis and approaches the United States, Japan, and South Korea. The material footprint and GHG embodied in machinery stock in developed regions are high, but we also observed the disproportional distribution within Europe. China is the region with the fastest growth in machinery stock. Its global share in terms of MF induced by in-service machinery has risen from less than 20% to over 30%, even though its per capita stock is only half of the United States. We do not observe signs of saturation of machinery stocks across countries, but because of depreciation, the accounting value of the present stock has saturated in some regions. Future analysis including scenario-based modeling will better identify circular economy and climate mitigation options for society's most considerable use of metals and develop better demand scenarios for materials.

Opportunities for Multi-Tier Global Supply Chain Emissions Mitigation

Wednesday, 5th July - 12:00: EEIOA cases 3 (B0.31 KOG)

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It is widely understood that scope 3 emissions can often account for the majority of a corporation's total carbon footprint. However, this knowledge provides little help or guidance from an emissions mitigation perspective as scope 3 emissions are generated by a complex web of energy and materials created by countless actors, multiple tiers of supply, and across many geographies. For corporations with a considerable share of scope 3 emissions, to what extent can cutting their suppliers' scope 1 and scope 2 emissions contribute toward mitigating their scope 3 emissions? Similarly, as governments and standards developers seek to address these relationships across the broader global economy, how far upstream and to which production-consumption systems must new policies and reporting protocols reach to compel upstream emissions reductions sufficient to meet global policy goals of stabilizing atmospheric concentrations of GHGs? In this study, we address these questions by compiling and analyzing newly and consistently constructed, high-resolution environmentally extended input-output models of four nations, the US, South Korea, Mexico, and China. Structural path analysis is conducted on each model, where multi-tier emissions estimates are organized to reflect the actor-level "scope" structure of the GHG Protocol. Early results indicate that, for the agricultural, mining and utility industries, 60% to 80% of total emissions reside in the combination of actors' scope 1 emissions (direct emissions of sector), scope 2 emissions (direct purchased electricity and steam), and the scope 1 and 2 emissions associated with direct purchased (tier 1) inputs. For manufacturing and service industries, the focus on this boundary can result in a similar degree of emissions reduction for some sectors but falls far short for most others. For those sectors, tier 2 or even tier 3 suppliers need to be involved. A weighting by final demand provides additional policy insight. In the US, for example, the service sector is the largest contributor to national GHG emissions, followed by the manufacturing sector. In South Korea, manufacturing is the largest contributor to national GHG emissions, whereas in China construction is the largest contributor. All these sectors are in aggregate dominated by their scope three emissions. In this talk, we present our methodology, results, and discuss the implications on recent efforts to revise the GHG Protocol's Corporate Standards and Guidance and the role of scope 3 in growing governmental reporting regulations.

Assessing the environmental and economic impacts of deposit-return schemes for beverage packaging with EEIO

Wednesday, 5th July - 12:15: EEIOA cases 3 (B0.31 KOG)

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The proposed Packaging and Packaging Waste Regulation in 2022 mandates that Member-states implement deposit-return schemes (DRS) for beverage packaging. Those in favour of DRS argue that these are the best option to achieve high recycling rates for beverage packaging, but these systems also tend to cost more than the standard models based on municipal waste collection and recycling.

In 2016, Rodrigues et al. proposed the EPRIO model. This model explicitly adds financing to the Waste Input-Ouput proposed by Nakamura and Kondo. The EPRIO was initially developed to assess the economic impacts of extended producer responsibility (EPR) schemes, but has been applied not only to Producer Responsibility Organizations (PRO), but also to consider other types of financing schemes and waste management sectors (e.g., coprocessing, hazardous waste management).

To model the environmental and economic impacts of the DRS, it was necessary to implement two important extensions to the EPRIO model. Firstly, it was necessary to consider multiple sources of funding. Contrary to EPR schemes, DRS are directly funded not only by producers through a producer's fee, but also by consumers through unredeemed deposit values. Secondly, deposit values are significantly higher than producer 's fees and therefore it is not enough to assume inelastic demand for beverages as it was done by Rodrigues et al. (2016) in their demonstrative example. The proposed presentation will explore these two theoretical developments as contributions to the application of EEIO in waste policy analysis.

The extended EPRIO model was then parametrized and used to estimate the environmental and economic impacs of a DRS for Portugal, which has been discussed at least since 2020, i.e. before the proposal of the PPWR. The parametrization had to be based on several assumptions and literature review, such as the type of collection activites and equipment, among other. Results show that the environmental impacts of a DRS can be positive (i.e., beneficial) if the reference scenario has a low PET collection rate and collection activites and logistics are mostly based on reverse logistics. However, these are weak assumptions and careful system design is needed to ensure to ensure net positive impacts. Regarding the economic impact, it was found that the DRS has negative economic impacts, mostly due to the cost borne by consumers due through unreedemed deposits which is chanelled to support collection activites that are capital-intensive. A decising factor is the share of beverages that are collected through reverse-vending machines vs. store clerks. The induced effects, i.e. effects arising from increased expenditure from salaries, are smaller when the system is based on reverse-vending machines. The most significant negative impact results from reduced consumption due to unredeemed deposits, which can amount to 20 million euros in the case of Portugal. Globally, it is estimated that the negative economic impact measured in GDP amounts to 45 million euros.

These results suggest that despite being the best option to achieve high recycling rates in key materials such as food-grade PET, DRS must carefully designed to minimize negative economic impacts. Proposals by the European Commission on these systems should be accompanied by more in-depth studies on their design.

IE and decision-making

Empirically grounded agent-based simulation of circular economy strategies: product circularity, consumer behavior, and environmental consequences

Wednesday, 5th July - 11:00: IE and decision-making (B0.13 KOG)

Ryu Koide [1], *Haruhisa Yamamoto* [2], *Keisuke Nansai* [2], *Shinsuke Murakami* [3]

1. Material Cycles Division, National Institute for Environmental Studies, 2. National Institute for Environmental Studies, 3. The University of Tokyo

Introducing new business models in the circular economy (CE), such as sharing and refurbishment, may significantly change system-wide consequences, including consumer behavior and environmental consequences. Although it is necessary to ensure that the improvement in circularity leads to environmental benefits avoiding backfire effects, a method that can assess both circularity and environmental consequences of multiple circular economy strategies still need to be developed. In addition, despite the importance of use-phase behaviors and product stocks, there has been a need for more research on consumer behavior to examine effective interventions for its diffusion. In this study, we developed an agent-based simulation model for assessing environmental consequences and product circularity of CE strategies endogenizing dynamic and bounded-rational consumer decision-making.

An agent-based model can represent consumers and products as agents so that it considers the heterogeneity of consumer behavior and product circulation and their mutual interactions. The consumer behavior model incorporated in the simulation model dynamically predicts the choice behavior of individual households for three types of decisions in CE: acquisition, repair, and discharge of products. Here, consumers only sometimes make a perfectly rational choice but gradually narrow down alternatives by formulating awareness and consideration sets. This occurs through information search (word-of-mouth and advertisements) in the social network and comparing expected utility and cognitive costs for considering an additional alternative. The model considered various product attributes, including price, manufacture year, ownership and circularity status, repair warranty, and social influence (conformity). The product circulation model incorporates the processes associated with introducing seven explicitly defined CE strategies (e.g., repair, reuse, refurbish, rental, sharing) and their combinations (e.g., rental of refurbished products). The product lifetime was modeled by a Weibull distribution that distinguishes between failure and relative obsolescence. The various processes in CE (e.g., parts production, refurbishing, repair, transportation) in each time step were stored as an foreground inventory, which can, in combination with background LCI data, dynamically quantify the environmental impacts and product circularity indicators. The simulation model is designed to be calibrated with empirical data, including choice experiments (conjoint analysis), questionnaire surveys on product lifetime (survival analysis), and exiting business operation and LCI data.

A simulation experiment with a hypothetical case study indicated the model's ability to successfully quantify the dynamic diffusion of new product services, its product flows and stocks (including Sankey charts), and greenhouse gas emissions throughout the simulation period of 30 years. Here, the model could be used for several purposes, including i) comparison of business models in terms of environmental sustainability (e.g., rental vs. sharing) and ii) comparison of promotional measures (e.g., price change, information provision, service level). In addition, large-scale survey data with a nationally representative sample in Japan was used to calibrate the simulation model. Here, consumers' part-worth utilities for product acquisition, repair, and discharge choices, product lifetime, the topology of the social network, and information search and consideration parameters were calibrated by the hierarchical Bayes method to account for heterogeneity among agents. A preliminary simulation experiment with a synthetic population based on the survey data identified the importance and effectiveness of endogenizing empirically grounded consumer behaviors in the assessment model of the circular economy. The proposed method is helpful for consequential LCA and circularity assessment of CE. It can support policymaking and the design of CE business models with both diffusion potentials and sustainability gains.

Integrated System Analysis of Urban Vegetation and Agriculture (URBAG): an interdisciplinary and participatory decision approach to evaluate the design and implementation of green infrastructures in urban environments.

Wednesday, 5th July - 11:15: IE and decision-making (B0.13 KOG)

gara villalba [1], ***David Camacho*** [2], ***Johannes Langemeyer*** [2]

1. *Universitat Autònoma de Barcelona (UAB,* ***2.*** *Universitat Autònoma de Barcelona*

Cities are implementing green infrastructures (GI) to address societal challenges such as climate change mitigation, natural disaster adaptation, and food security. However, we lack the tools and understanding to systematically address the trade-offs and synergies that GIs can create in urban environments (e.g., a GI implemented for improving urban resilience can create or exacerbate inequalities). We propose the Integrated System Analysis of Urban Vegetation and Agriculture (URBAG): an interdisciplinary and participatory decision approach that is geographically explicit to evaluate the design and implementation of green infrastructures in urban environments. It is founded on multi-criteria decision analysis and compares the urban space with and without the GI by employing both exposure and sensitivity analyses. The framework has four phases: 1) Defining the aim, scope, and scale of the assessment (2) Selecting criteria and indicators that line up with the aim of the assessment for the GI, (3) calculating the indicators, and (4) analyzing and determining the impacts according to the weights selected by relevant stakeholders. To illustrate URBAG, we assess various scenarios of peri-urban agriculture in the Metropolitan Area of Barcelona with the overall aim to increase local crop production, restore abandoned lands, and reduce heat wave effects. For the assessment, four criteria were analyzed: (1) Heat Conditions and Exposure, (2) Spaces for cultural and recreational experiences, (3) Food self-sufficiency and (4) Environmental impacts of fertilizer use. The indicators were temporally and geographically determined based on atmospheric model simulations and life cycle assessment. Results showed that an increase in agricultural areas can reduce daytime temperature during heatwaves (up to 1.7ºC), and how these reductions where partially located in areas with large elderly populations, a vulnerable group to heat exposure. The accessibility to green spaces for recreational experiences was also improved by the increase of agricultural areas, but most of these new accessibilities were not located in sensitive areas with high population density. In the case of food self-sufficiency, the scenario with the greatest agricultural area is expected to meet up to 12.8% of the fresh produce demand of the city, while the crop production location does not match the areas with the highest demand of food within the city. Finally, freshwater eutrophication associated to increased fertilizer use due to more agriculture proved insignificant because of the very low value of P equivalent emitted due to short river segments, but the biodiversity indicator points out a significant exposure in already mid-low biodiversity river basins. This case study illustrates the usefulness of URBAG in analyzing the spatial distribution of the impacts of green infrastructure and how it affects the environment and sensitive populations, transferring the scientific knowledge to urban policy and governance for successful GI implementation.

Measuring the impact of environmental policy on the sustainable supply of critical materials

Wednesday, 5th July - 11:30: IE and decision-making (B0.13 KOG)

Karan Bhuwalka [1], ***John Ryter*** [2], ***Elsa Olivetti*** [1], ***Richard Roth*** [1]

1. Massachusetts Institute of Technology, 2. United States Geological Survey

As clean energy technologies drive up demand for various metals, it is vital to ensure adequate material supply while restricting environmental impacts from mining. We build a market model that simulates metal demand, mine opening and operations, reserve development, and price feedback. Using data on real mining projects, we demonstrate the effect of environmental policies on metals markets. We demonstrate via a case study of the copper system how carbon taxes, water stress and the growing demand for metal impact future material prices and quantity available. We use the model to comment on how price premiums might develop for metals with certain characteristics such as i) "green metal" or ii) metals sourced from areas with lower water risk. By demonstrating the impact of various types of policies on metals markets, we gain vital insights for policymakers. For example, we find that carbon taxes lower emissions from mining, but they threaten resource availability by reducing mine opening and increasing mine closing. Policymakers should therefore combine carbon taxes with incentives for the mining of critical materials

Data driven decision-making for circular economy implementation in agro-food systems

Wednesday, 5th July - 11:45: IE and decision-making (B0.13 KOG)

Bart van Hoof [1], ***Andres Medaglia*** [1], ***Alfaima L. Solano-Blanco*** [1], ***Carolina Mendez*** [1], ***Juan Riaño*** [1]

1. *Universidad de los Andes*

Sustainable supply for food security, to feed the growing world population, represents a major challenge to advance the global agenda of SDG, including the transition towards a circular economy. A growing body of literature is developing concepts and documenting opportunities of the Circular Economy for agro-food systems. So far, academic inquiry about methodologies for the practical implementation of circular economy models at a farm level remains theoretical. This research proposes a transdisciplinary data-driven research approach for the evaluation of circular economy alternatives in agro-food systems. The proposed method combines data-driven scientific methods for the simulation of critical resource flows part of the agronomic production system, and multi-criteria analysis supporting decision making. Training and feedback of farmers make part of the transdisciplinary methodology, that was tested in a case study of the cacao agro-food system, of diverse associations in Meta Colombia. The data-driven evaluation considered four differentiated circular economy scenarios including, composting, vermicompost, drip-irrigation, and the valorization of cacao husk. Results prioritize the implementation of 4 circular practices based on cost-benefit and resource efficiency. In addition, the transdisciplinary method enhanced the capacity of farmers including decision-making for circular economy implementation. This research contributes to circular economy literature by proposing transdisciplinary methods for data-driven evaluation of circularity practices and supporting decision-making for implementation. Transdisciplinary aggregates validation steps in analytic modeling techniques.

Analysis and Optimization of Energy Coproduct Opportunities within an Industrial Park: A case study of the Bécancour Industrial Park

Wednesday, 5th July - 12:00: IE and decision-making (B0.13 KOG)

***Leo Lamy-Laliberte** [1], **Simon Barnabé** [2], **Normand Mousseau** [3], **Jean-Marc Frayret** [4]*

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In recent years, there has been a growing interest in the use of quantitative tools for the analysis and optimization of industrial symbioses and by-product exchange networks. However, while there is a significant amount of literature on the optimization of material exchanges, there is less literature on the optimization of energy exchanges. This research addresses this gap by focusing on the specific problem of optimizing energy exchanges in the Bécancour industrial park, Québec, Canada. The analysis of literature shows that existing tools do not fully address all necessary considerations, such as long-term investment and profitability for individual actors. To address this issue, we extended the capabilities of a model and validated the resulting tool in the specific case of the Bécancour industrial park. More specifically, the project adapts a mixed integer linear programming (MILP) model called AnyMOD.jl to optimize industrial symbiosis and energy by-product exchange. For instance, the proposed model has been enhanced to incorporate forecasting of future energy outflows through the application of concepts from time series analysis. Additionally, constraints have been added and modified to reflect the properties of physical infrastructure required for facilitating energy exchanges. Furthermore, the model has been adapted to include a stochastic approach, not present in the original.

Our goal is to identify the optimal network of economically viable energy by-product synergies between industrial companies. The optimization model considers various aspects such as the long-term energy consumption profile of companies, the supply and demand of energy by-products within the industrial park and economic factors associated with the engineering requirement of the implementation of such a network including capital and operational expenditures of infrastructures. In other words, the model finds the optimal composition of an energy exchange network by combining energy conversion technologies, energy storage solutions, possibilities of mutualizing infrastructure, energy by-product flows treatment and the potential of adding complementary companies.

To conduct the research, multiple interviews were conducted with industrial actors within the Bécancour industrial park to gather data about their energy and production profile. This information was then used to model their energy by-product flows over a 10-year period. Other parameters used in the algorithm include investment and operation costs associated with the exchange of energy by-products and multiple functions depicting the dynamic nature of the innovation in terms of conversion and storage technologies.

The output of the model is then further investigated in a techno-economic study that provides valuable insights into the technical feasibility and profitability thresholds for the industrial park's actors, making it a valuable tool for decision-making and planning for industrial parks looking to implement circular economy strategies and significantly reduce their environmental impact.

Preliminary results show that the adjusted model can find an optimal network for economically viable synergies leading to a significant reduction in greenhouse gas emissions and an increase in energy efficiency. In specific circumstances, some synergies can even have the potential to increase the maximum production capacity for certain industrial companies, giving the solution the potential to increase competitiveness.

New indicators and measures

Developping green supply chains in islands through circular desalination. The case study of Chios Island, in Greece

Wednesday, 5th July - 11:00: New indicators and measures (B0.41 KOG)

Dimitrios Xevgenos [1]**, *Riccardo Longo*** [2]**, *Nogues Ollier*** [2]**, *Marina Montero*** [2]**, *Niels van Linden*** [3]**, *Petros Kalogerakis*** [4]

1. *Delft University of Technology,* ***2.*** *Clean Energy for EU Islands Secretariat,* ***3.*** *LENNTECH BV,* ***4.*** *Municipal Company for Water and Sewage of Chios Island*

Energy transition in islands constitutes a major challenge, as the vast majority is dependent almost 100% on imported liquid fossil fuels (Katsaprakakis et al, 2022). Further to that, islands often are water deficient and are thus dependent on seawater desalination to supply their drinking water needs. In the case of Cyprus island, as much as 70% of the drinking water supply comes from desalination, but this comes at a certain environmental cost: approx. 169 ktons of CO_2 emissions and 100 million m3 of wastewater brine are being emitted per year to the environment (Xevgenos et al, 2021). At the same time, this puts extra pressure at the energy supply system, as it requires approx. 241 GWh of electricity, which represents almost 50% of the total electricity consumption for industrial purposes of the island. These observations led us to the following research questions: (i) what is the role of desalination in the energy transition of islands and (ii) how can the wastewater of seawater desalination can be used to develop local supply chains through the recovery of secondary raw materials.

To address these questions, we used a case study research approach, examining the case of Chios Island in Greece. First we mapped the desalination plants and retrieved information about the water sources and uses. Secondly, we estimated the renewable energy (RES) potential of the island, i.e. solar and wind energy, developing wind and solar resource maps, necessary to identify strategic areas on the island for RES exploitation. To do so suitable software tools were used, Global Solar Atlas 2.0 and WindPro respectively. Finally, in close collaboration with local stakeholders we identified the main chemicals needed (caustic soda) together with the respective quantities and market specifications. We found out that in Chios, desalinated water (8,000 m^3/day) comprises an important share in the total drinking water supply for the island, covering almost 15% of the total water needs. Two maps on Global Horizontal Irradiance and PV output were developed indicating the areas of the island with the best potential, and multiple maps on wind potential at different heights and areas. A Circular & Decarbonized Desalination system was finally designed, being driven by RES and being able to recover the necessary quantity of caustic soda that is needed locally, that is 11,000 kg per year. Suitable locations for this system were also proposed taking into account different criteria.

Acknowledgement

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Evaluating the impact of different CE strategies on future bulk and scarce material demand in Austria

Wednesday, 5th July - 11:15: New indicators and measures (B0.41 KOG)

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The Austrian government strives to achieve climate neutrality in 2040. At the same time, it committed itself to an ambitious circular economy strategy to achieve 7 t/cap material footprint by 2050, which equals an 80% reduction compared to the most recent data. Beyond vehicle fleet electrification and decarbonisation of heating systems, as well as thermal insulation and greening of electricity production, narrowing, slowing, and closing material loops are key strategies to achieve this ambitious resource use reduction. Naturally, such a mass-based sustainability indicator causes the focus to lie on narrowing bulk material flows such as aggregates and concrete. However, the technology transition in the mobility, building, and energy sectors will require substantial amounts of scarce materials including rare earths that are less relevant for the quantity of material flows but currently irreplaceable for certain key technologies.

This ambiguity of reducing material demand while simultaneously extending the range of application of technology-critical elements is reflected in CE strategies. While some strategies aim to reduce material consumption and emissions primarily via technological solutions such as recycling, material flow narrowing sufficiency strategies, on the other hand, have an overall reduction effect for both bulk and scarce material flows. For example, fleet electrification, as a technological solution, will reduce GHG emissions while simultaneously increasing demand for scarce materials such as lithium or neodymium in vehicle motors and batteries as well as for wind and solar power to provide the power for e-mobility. In contrast, car sharing, as an exemplary strategy of the latter type, does not reduce asphalt demand. It does, however, reduce demand for rare earths as a smaller vehicle fleet and consecutive lower green power capacities will be needed to provide the same transportation services.

Because technological decisions today will have far-reaching implications for future material consumption and will cause certain path dependencies, understanding the material demand implications of each strategy is key. To this effect, a stock-driven prospective scenario modelling will be conducted and different contrasting scenarios will be discussed in terms of their impact on both bulk and scarce material flows: One scenario puts the emphasis on technology-driven decarbonisation and recycling, the other more sufficiency-driven scenario combines decarbonisation with a far reaching circularity strategy which narrows and slows material flows before recycling loops are closed. By tracing the effects of measures on the consumption of materials at sectoral level, this research will give further insights into possible conflicts, trade-offs, synergies, and priorities for steering the material flows towards the ambitious 80% reduction of the material footprint as well as a reduced dependency on scarce materials as foreseen in the Austrian government's circularity strategy.

The power of networks: A field data analysis of geographic network effects in the circular economy

Wednesday, 5th July - 11:30: New indicators and measures (B0.41 KOG)

Christoph Ratay [1]

1. *Technical University of Munich*

Product Service Systems (PSS) that replace ownership and offer a combination of products and services instead (Bocken et al., 2014; Tukker, 2015) apply circular business model strategies to slow resource use (Bocken et al., 2016). As PSS providers benefit from intensified use of their own assets, reduced resource use, and asset longevity (Bocken et al., 2014; Kjaer et al., 2019; Lüdeke￾Freund et al., 2019; Tukker, 2015), they have the potential to align financial incentives with environmental objectives. Research on motivators of and barriers to non-ownership forms of consumption such as PSS highlights the need to establish sufficiently large supply networks to attract demand by consumers (Wirtz et al., 2019). If this is not the case, consumers may be discouraged due to perceived product scarcity (Lamberton and Rose, 2012) and increased complexity of use (Hazée et al., 2017, 2020). Thus far, the effect of increased network density in circular, non-ownership business models is primarily established conceptually (Wirtz et al., 2019) or tested by empirical studies working with qualitative data (Habibi et al., 2016; Hazée et al., 2017, 2020) or stated preference methods (Habibi et al., 2016; Lamberton and Rose, 2012). However, revealed preference evidence based on field data capturing actual behavior is scarce. In response to this research need, this paper uses a large field dataset covering over two years of activity data of a system for reusable takeaway food containers to address the following research question: How does geographic network density affect consumers' system adoption and system use in the circular economy?

Two different density metrics commonly applied in research on food environments are used to measure the system's geographic network density around participating restaurants: The sum of inverse distances of a restaurant to all other participating restaurants (similar to Harrison et al., 2011) and the number of stores in a 1km buffer zone surrounding the restaurant (similar to Currie et al., 2010). Based on fixed effects Poisson panel models with both variables, this paper finds statistically significant and economically meaningful positive effects of increased geographic network density on acquiring new system users. Notably, results show that effects of increased geographic network density on user acquisition are positive across the entire relevant range of network density, but marginal effects diminish as networks get denser. In terms of frequency of use, no consistently significant effects of geographic network density are identified. These results contribute to the literature on network effects in multisided markets and in the circular economy by presenting field evidence of the importance of indirect, cross-side network effects on consumer adoption. Moreover, these findings encourage circular economy practitioners and policymakers to foster circular economy adoption by consumers through geographically dense supply networks.

Municipal Circular Economy Indicators: Do They Measure the Cities' Environmental Ambitions?

Wednesday, 5th July - 11:45: New indicators and measures (B0.41 KOG)

Mira Kopp [1], ***Anna Petit Boix*** [2], ***Sina Leipold*** [3]

1. Friedrich Schiller University Jena, 2. Universitat Autònoma de Barcelona, 3. Helmholtz Centre for Environmental Research

Circular economy is gaining traction in cities as an approach to reducing their local and global environmental impacts. However, the mitigation potential of circular economy strategies is increasingly being questioned. To ensure the implementation of legitimate strategies that align with the cities' goals, governmental practice needs relevant environmental monitoring tools. We reviewed 30 municipal circular economy policies from cities in high-income countries in Europe, the Americas, and Oceania to assess the relevance of their indicator sets with regard to their major environmental concerns. To do so, we conducted a qualitative analysis of policy documents published in more than seven languages until May 2021. We collected (1) the city's environmental goals and concerns, (2) the circular strategies suggested with regard to these goals, and (3) the indicators used to monitor progress. The review reveals a broad spectrum of circular city policies spanning waste management, local economic development, environmental sustainability, and climate action strategies. Among the most prominent concerns are climate mitigation and securing the local availability of resources, but overall, very diverse environmental targets could be identified – some of these aiming at local impacts such as air quality and public health while others envision global impacts such as biodiversity conservation and intergenerational justice. While greenhouse gas emissions of territorial scope are frequently monitored, the indicator sets mostly ignore that climate mitigation is targeted at a footprint scope. Moreover, the sets mostly lack indicators to monitor other environmental pressures and impacts. Transdisciplinary cooperation is needed to improve the applicability of scientifically developed urban footprint models to municipalities.

In Search of Lost Time - Measuring Material Services and Ultimate End at the Macro Level

Wednesday, 5th July - 12:00: New indicators and measures (B0.41 KOG)

***Piroska Harazin* [1], *Mihály Dombi* [1], *Andrea Karcagi-Kováts* [1], *Faisal Aldebei* [1]**

***1.** University of Debrecen*

The study of material services is an emerging topic in socio-economic metabolism research. Studies involving specific processes, such as illumination (Whiting et al. 2020), transportation (Virág et al. 2021; Carmona et al. 2021), have gained prominence over the past few years. Tanikawa et al. (2021), among other scholars, have made significant strides on the topic, however, conceptualizing, and quantifying the stock-flow-service (SFS) nexus at the macro level, remains immature.

We draw a parallel between Daly's ends-means spectrum (Daly, 1991) and the SFS nexus as a basic framework. Daly's concept of ultimate ends and means provides us with a framework to analyse material services. In this framework, material services are to be viewed as connecting intermediate ends and Ultimate End, where the Ultimate End refers to an intrinsically good aim for a society that motivates all the resource utilization fluxes and accumulations within the means-ends spectrum. The framework highlights the macroeconomic measurement methods used so far in the socio-economic system (e.g. GDP, material footprint); but also points out a gap in the case of material services and Ultimate End measurement. Simply aggregating micro-scale material services does not provide valuable results because of the sector-specific variables that define the ultimate and intermediate ends.

Daly provided some implicit examples of Ultimate End as follows, "Leisure, silence, contemplation, or conversation, are made more difficult by the production-consumption drive" (Daly, 1991). Following this logic, we assumed that time spent on participating in society – which relates to Daly's Ultimate End, because guaranteeing the "survival of the entire evolutionary process" (Daly, 1991) to develop a society in qualitative terms – multiplied by Life Expectancy, can characterize the Ultimate End of a person in the society, as a reverse stock indicator (UE).

Using the IPAT (Impact, Population, Affluence, Technology, I=PxAxT) logic, we defined five indicators as effects (Natural Capital, Throughput, Stock Intensity, Material Productivity, Material Services) based on Daly's entire means and ends spectrum, through which equates the time-based value of Ultimate End.

Time-based value of Ultimate End (UE) ≡ Natural Capital x Throughput x Stock Intensity x Material Productivity x Material Services.

We used land cover data, the value of domestic extraction, GDP, total stock data, and time-use surveys to measure these indicators. For 17 European countries, we compared these indicators, and we can see that level of Material Productivity (highest in the Netherlands and lowest in Norway) can mainly influence the country differences in UE (Ireland has the highest value with 36.68 years and Hungary has the lowest with 28.04 years).

Additionally, for the US, we made a decomposition analysis – to see how changes in these indicators can influence the reverse stock temporally –, which shows, that the time-based value of Ultimate End decreased by 5% between 2003 and 2016, which is mostly influenced by decreasing values of indicators, which tendency is only compensated by Material Productivity.

The importance of policy tools that selectively limit stock accumulation based on capital items' usefulness and material efficiency is unquestionable. Therefore, the social benefits derived from different types of capital should be assessed. Implementing well-targeted fiscal policy and establishing other institutional improvements requires recognizing the benefits of distinct policy interventions, as well as their sectoral impacts and effects on different capital types.

Outline of a material stock-oriented policy mix towards sustainability

Wednesday, 5th July - 12:15: New indicators and measures (B0.41 KOG)

Mihály Dombi [1], ***Piroska Harazin*** [1], ***Andrea Karcagi-Kováts*** [1], ***Faisal Aldebei*** [1], ***Zhi Cao*** [2]

1. University of Debrecen, 2. University of Antwerp

The essential role of material stock in the socio-economic system has been recognized for a long time within the community of ecological economists and industrial ecologists for their determinant nature about material extraction, flows, and waste streams (Lanau et al., 2019). Recently, the quality of services delivering the core basics for human well-being has been acknowledged to depend on material stock (e.g., Carmona et al., 2017). Given the insufficiency of market-based solutions for reducing carbon emissions (Green et al., 2021), among other ecological crises, one could confidentially state that the economic subsystem requires substantial remodeling to avoid the worst scenarios of the future.
We have constructed a four-step policy action plan to reduce the pace of material stock accumulation dramatically, consisting of

1. reduction of the savings rate through wealth or capital income taxes,
2. spatial planning interventions,
3. the government-led housing market, and
4. reduction of the mandatory writing-off rates for capital assets.

Our proposition utilizes on the findings of a panel analysis of 150 countries between 1980 and 2016. According to these results, the savings rate reinforces the accumulation of the material stock, as one percentage increment of the savings rate is associated with a 0.85 percent rise in total concrete stock if everything else is held constant. GDP, of course, affects the stock positively as well. The bond between the GDP and the stock is strong enough, as every percent GDP growth evokes 0.44 percent of predicted stock increment, ceteris paribus. However, the net return on capital negatively correlates with the stock, with a 0.22% drop in predicted stock dynamics in case of a 1% rise in returns.
These results help to imagine the challenge for the future: Society should meet the housing, consumption, innovation, community participation, and other needs while maintaining, or rather accepting, a nearly monopolized capital/material stock market. However, this deliberation of this market contradicts the sustainability transition, as it calls for substantially reducing stock accumulation. Four steps are, therefore, carefully constructed to combat this dual challenge, considering differences in the demand and supply of three main types of material stock, namely residential, non-residential, and civil engineering stocks.
Spatial planning conditions (step (*2*) here) are proven to form the amount and distribution of the material stock accumulation in time (Göswein et al., 2017; Gao et al., 2020; Dombi, 2022). Complementary, we have tested the joint occurrence of steps (*1*) and (*4*), i.e., a simultaneous drop in savings and depreciation in a panel of 120 countries, to evaluate its potential in deceleration material stock accumulation. We have estimated the amount of material stock to be lower by an average of 7-10% in five years after a country shifted its savings and depreciation trends into a descending trajectory, depending on the stock type.
In addition, we observed that this moderated accumulation process did not accompany an economic recession. Furthermore, synergies between the enforced halt in stock accumulation, and social equality, well-being, and community aims have been revealed.

Mobility

Influence of Urban Form on Car Ownership, Mode Choice, and Travel Distance in European Cities

Wednesday, 5th July - 11:00: Mobility (C1.31 KOG)

Peter Berrill [1]***, Felix Wagner*** [2]***, Nikola Milojevic-Dupont*** [2]***, Florian Nachtigall*** [2]***, Aneeque Javaid*** [3]***, Felix Creutzig*** [2]

1. *Technical University Berlin,* ***2.*** *Mercator Research Institute on Global Commons and Climate Change (MCC), Berlin,* ***3.*** *IIASA*

Steady growth in global greenhouse gas emissions from transport is driven by growing demand for car travel. Cities hold large potential to reduce energy demand and emissions from mobility through encouraging shorter travel distances and sustainable travel modes. In European cities , personal cars still dominate travel, facilitating continued growth of transport emissions and having negative implications for numerous other dimensions of sustainability. A growing body of research investigates linkages between urban form and mobility, mostly using aggregate data in multiple cities, or disaggregated data for individual cities. Here, we compare urban travel patterns and influences of urban form at spatially disaggregated scale across nineteen cities in four European countries using statistically advanced methods. We enrich travel survey data with metrics describing local urban form. We compare car ownership and travel patterns across cities and use supervised machine learning to explore influences of urban form and other features on mode choice, car ownership, and trip distances. Residential proximity to the city center is identified as the greatest enabler of sustainable urban mobility. Future residential development should be concentrated near to urban centers. Overall city size is important, as occupants of small and medium-sized cities have higher car ownership and use than large cities, motivating increased attention on sustainable mobility transitions outside of large cities. We highlight targeted solutions to increase access to sustainable mobility for trips involving children, and for longer urban trips. Our results confirm that urban planning is a key instrument for increasing sustainability of land transport.

Air quality benefits from decarbonization scenarios for the U.S. light-duty passenger vehicle fleet from 2022-2050.

Wednesday, 5th July - 11:15: Mobility (C1.31 KOG)

Jean Schmitt [1]***, Marianne Hatzopoulou*** [1]***, I. Daniel Posen*** [1]***, Heather L. MacLean*** [1]

1. Civil and Mineral Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario, M5S 1A4

Greenhouse gases (GHGs) are often emitted together with other pollutants, such as nitrogen oxides (NOx), sulfur dioxide (SO2), and fine particulate matter (PM2.5), which have localized and immediate impacts on the health of exposed individuals, and their quantification can benefit the perceived efficiency of GHG mitigation strategies. Co-benefits for transportation GHG mitigation policies are widely studied, but generally model a snapshot in time with a focus on narrow geographies such as cities or small regions. In contrast, policy timing and diversity of geographical application have a significant impact on resulting *cumulative* health benefits, requiring national scale analysis that accounts for the dynamics of vehicle fleet turnover over time. We develop a computational model to quantify the health benefits from passenger vehicle electrification strategies across the U.S. with a breakdown by county, by combining the Motor Vehicle Emission Simulator (MOVES) and the Co-Benefits Risk Assessment tool (COBRA) developed by the U.S. Environmental Protection Agency, together with the Fleet Life Cycle Assessment and Material Flow Estimation (FLAME) model, which quantifies fleet turnover and GHG emissions of the U.S. light duty fleet. The model includes the airborne pollutants from additional electricity production for vehicle charging and takes into account changes in PM2.5 from brake and tire wear associated with vehicle electrification.

Our baseline scenario follows the 2022-2050 fleet composition forecast from the 2022 Annual Energy Outlook (AEO) published by the Energy Information Administration. We apply an aggressive vehicle electrification policy to the baseline scenario, targeting 100% battery electric vehicle sales by 2035, corresponding to Zero Emission Vehicle (ZEV) targets in California and other jurisdictions. To assess the impact of implementation geography on health benefits, we first apply the electrification scenario to the states participating in the ZEV program, and then derive a hypothetical scenario whereby all U.S. states follow the program. The impact of implementation timeline is investigated by postponing the year the targeted sales share is reached. Fleet renewal in all scenarios follows annual age-based vehicle scrap-rates. Electricity scenarios are bounded assuming charging relies on either the current (2022) U.S. grid or a fully low-carbon grid throughout the study period, with additional scenarios to be added if bounding results are impactful.

The cumulative monetized health benefits of the investigated policies are reported relative to the baseline scenario for the period 2022-2050. According to preliminary results, the geographically limited electrification policy (with low carbon electricity) is estimated to result in $3.6B health benefits, while with the ambitious nationwide electrification policy the benefits reach $23B. Policy timing plays a significant role, as a delay of 2 years was estimated to reduce the cumulative benefits of the nationwide electrification policy by $5B over the 2022-2050 period ($6B for a 5-years delay, $10B for 10 years and $15B for 15 years).

Although annual emissions decrease considerably in the baseline scenario owing to fleet renewal alone, these initial results show that fleet electrification provides substantial additional health benefits; total benefits are highly dependent on the implementation timeline and geography. Future work will focus on investigating the contribution of the different pollutants, especially emissions from brake and tire wear. Alternative scenarios featuring downsizing, reduction in vehicle miles travelled and fleet size will be assessed.

Meeting U.S. light-duty vehicle fleet climate targets with electric vehicles and electrofuels

Wednesday, 5th July - 11:30: Mobility (C1.31 KOG)

***Dijuan Liang* [1], *Alexandre Milovanoff* [1], *I. Daniel Posen* [1], *Heather L. MacLean* [1], *Jean Schmitt* [2]**

***1.** Civil and Mineral Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario, M5S 1A4, **2.** Civil and Mineral Engineering, University of Toronto, 35 St. George Street, Toronto, Ontario, M5S 1A4 Canada*

Mitigating greenhouse gas emissions (GHG) from the U.S. light-duty vehicle (LDV) fleet to meet climate targets cannot solely rely on electric vehicles (EVs). A potential complementary strategy is to replace conventional fossil fuels with electrofuels (e-fuels), which can be produced from electrolysis-based hydrogen and carbon capture-based CO_2 through chemical synthesis. This study is particularly interested in e-gasoline, a drop-in e-fuel compatible with existing conventional vehicles and fuel infrastructure that can be produced from the Fischer-Tropsch pathway or methanol-to-gasoline pathway. Both fuel pathways are now in the technology demonstration stage; the first pilot plant started to operate in Chile in 2022 and produces 130k L/yr of e-gasoline using hydrogen from wind-based electrolysis and CO_2 from direct air capture. Life cycle assessments (LCAs) have shown that e-gasoline can have lower GHG emissions than conventional gasoline (per unit of fuel) if produced with low GHG intensity feedstocks and energy sources. At the fleet level, the required contribution from e-gasoline depends on the projected scenarios of EV deployment and the resulting GHG emissions left to mitigate. However, existing fleet-level assessments have not captured the interaction between EV and e-gasoline deployment and U.S. studies have not evaluated e-gasoline's role in meeting climate targets.

To fill these gaps, this study aims to 1) determine production characteristics that make e-gasoline advantageous in GHG mitigation through fuel-level and vehicle-level LCAs; and 2) use fleet-level LCA to understand how deploying e-gasoline in the U.S. LDV fleet can help reach ambitious climate targets, with a focus on required e-gasoline production volumes and the associated demand for feedstock, renewable electricity as well as critical materials in water electrolyzers and electricity generation. At the fuel and vehicle levels, variations in production pathways, energy sources, and CO_2 sources are evaluated. E-gasoline production is then incorporated into the FLAME (Fleet Life Cycle Assessment and Material-Flow Estimation) model to estimate the life cycle GHG emissions of the U.S. LDV fleet to 2050. A backcasting analysis is conducted to determine the required e-gasoline levels to meet 1.5 and 2 °C climate targets by 2050 under three EV deployment scenarios with different deployment levels and charging electricity sources.

Results show that the GHG intensity of e-gasoline is most sensitive to the GHG intensity of the electricity used in electrolysis. At the fleet level, deploying e-gasoline produced from fully renewable energy has the potential to assist the U.S. LDV fleet to meet 1.5 and 2 °C targets but would require extremely aggressive production ramp-up – with peak production ranging from 10-400 billion L/yr by around 2040 depending on the EV deployment scenario. Producing the required volumes for the 2 °C target is expected to be challenging due to the early stage of the e-gasoline industry, demand for captured carbon (0.3-1.1 Gt/yr at the peak – 12-44 times U.S. production level in 2019), water electrolysis-based hydrogen (5-146 Mt/yr at the peak – 50-1460 times U.S. production level in 2020), renewable electricity (0.3-8 PWh/yr at the peak – 0.3-9 times U.S. renewable electricity generation in 2022) and critical materials (7-46% of world reserve of iridium).

How to plan shared mobility for a sustainable transportation system?

Wednesday, 5th July - 11:45: Mobility (C1.31 KOG)

***Hao Luo* [1], *Hua Cai* [1]**

***1.** Purdue University*

The transportation system in the U.S. has caused a lot of issues with environmental sustainability due to its car-oriented development. The transportation system has become the largest GHG emission sector in the U.S. economy. The high vehicle-mile-traveled (VMT) in residents' daily life also leads to traffic congestion, noise, and air pollution. Shared mobility, including bike-sharing, shared e-scooter, and ride-hailing services, was seen as a promising revolution to resolve the sustainability issues in the current transportation system. The benefits of shared mobility usage mainly come from replacing car trips and first/last-mile connections with public transit system. However, existing studies have shown that shared mobility riders often use it to substitute other green travel modes (e.g., walking and bus), not as planners wish. If shared mobility is not well-planned and not gains enough emission mitigation benefits, the embedded carbon footprints in shared mobility operation, such as vehicle rebalancing, dispatching, and battery charging, could even turn it into an environmental burden for a city. How to plan shared mobility in terms of its pricing and availability to minimize carbon footprints and maximize emission mitigations (private car replacement and transit integration) at the same time?

To find the best practice of shared mobility planning for environmental sustainability, we first need to understand what key factors could motivate people's travel mode choice to shift from private car to shared mobility. We build a discrete choice model that considers utilities of nine travel modes (traditional modes, shared mobility, and multi-modal systems) for different groups of travelers based on a stated-preference survey. An agent-based transportation simulation model is then developed to estimate the environmental impacts of shared mobility development, considering individual travel demand, mode choice decision rules (discrete choice model), socio-demographic attributes, and shared mobility's operations. Results will be analyzed based on a set of scenarios, which are various on pricing structure, fleet size, and vehicle siting, to find the optimal development plan for shared mobility. This study can provide practical implications for transportation planners to design a sustainable shared mobility.

Sustainable Resource Assessments of Residential Building and Transportation Infrastructures in Vietnam: From Stock-Flow-Service nexus Perspective

Wednesday, 5th July - 12:00: Mobility (C1.31 KOG)

Thi Cuc Nguyen [1], ***Junbeum Kim*** [1]

1. *CREIDD Research Center on Environmental Studies & Sustainability, Interdisciplinary research on Society-Technology-Environment Interactions, University of Technology of Troyes, Troyes, France*

Regarding promoting sustainable use of our natural resources, countries report regular national accounts for material stocks and flow, but developing countries modest still need to grow. In this research, we apply Stock-Flow-Service (SFS) nexus to assess the sustainable resource use in providing shelter, thermal comfort, and transport services in Vietnam from 2004 to 2019. We consider the material stocks and flows involved in expanding and maintaining residential buildings, roads, main household products, and road vehicles. We quantify the energy flows and emissions linked to shelter, thermal comfort, and road transportation services. We analyze and compare several SFS indicators that show the stock-flow-service relations. Our results show that the stocks of constructions and products increased significantly, and most material inflows were used to expand existing stocks during 2004-2019. The stock intensity for shelter remained steady at about 1,400 kg/ while it increased from 4 to 7.5 kg/pop cooling degree days for thermal comfort services and decreased from 86 to 43 kg/freight-km equivalent for transportation services. The energy and emission intensities for thermal comfort services increased by 23 and 38 times, respectively, while the values for road transportation services were reduced by half over the study period. We discuss challenges and policy implementations linked to material and energy resources used for shelter, thermal comfort, and transport services in Vietnam. Considering stock-flow-service interconnections can shed light on Vietnam's accounts for material stocks and flows and support the policy implications on national sustainable resource assessments.

Water 2

Enhancing household water consumption prediction by the water-energy nexus concept: a case of Beijing, China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wednesday, 5th July - 11:00: Water 2 (B0.16 KOG)

Zonghan Li [1]***, Yi Liu*** [1]***, Chunyan Wang*** [1]

1. *Tsinghua University*

The rapid increase in residential water use is attracting attention. Due to rapidly growing urban settlements, household water consumption is expected to increase significantly by 2050. The challenges posed by the surge could be better addressed by predicting future water consumption. However, the estimation of residential water demand remains one of the most challenging problems in cities to date.

This study aims to enhance household water consumption predictions using the water-energy nexus concept, i.e., considering energy use (EU) features and electricity consumption (EC) features in the model, to better understand the household water-energy nexus. We designed a stepwise-like approach that can compare the predictions before and after considering EU and EC, utilize household-level data and establish four annual water consumption prediction models with the stepwise-like approach. The four models were applied to data from 1320 surveyed households in Haidian and Tongzhou Districts in Beijing, China, in 2020 by employing a traditional statistical technique, OLS, and machine learning techniques, including random forest (RF) and extreme gradient boost (XGBoost).

The results illustrate the importance of the water-energy nexus in enhancing the goodness of fit and accuracy of household water predictions: models adding EU&EC and EU had lower root mean square errors (RMSEs, 9.0% and 5.4% on average, respectively), lower mean average percentage errors (MAPEs, 8.8% and 5.5%) and higher coefficients of determination (R2, 30.4% and 20.2%) than the basic model; the total importance of EU was 3.8% higher than that of water use features. The role of machine learning techniques in the predictions was also revealed, as XGBoost performed the best among the three techniques. Compared with other predictions with similar spatial scales, nature of data and sample size, the R2 of this study was also improved by at least 23.8%.

In short, the water-energy nexus concept not only enhanced the performance of household water consumption predictions in this study compared with previous works, but also provides novel and efficient improvement approaches for future related studies. The enhancements can help us reach a better understanding of the household water-energy nexus and facilitate better infrastructure planning and management in cities.

Towards a circular economy of water- Integrated process modeling, technoeconomic analysis, and life cycle assessment for anaerobic membrane bioreactor platform for wastewater management

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wednesday, 5th July - 11:15: Water 2 (B0.16 KOG)

Madison Kratzer [1], ***Prathap Parameswaran*** [2], ***Vikas Khanna*** [1]

1. University of Pittsburgh, 2. Kansas State University

One of the key tenets of the circular economy is minimizing resource extraction by fully recovering resources from streams that are traditionally considered waste. Wastewater streams from different sources contain recoverable products such as energy and nutrients. Recovering these resources offers a pathway for minimizing the extraction of virgin resources its associated environmental impacts. Nutrients such as biologically active nitrogen and phosphorus derived from waste streams are of particular interest as these are typically obtained from non-renewable resources with high life cycle environmental impacts. Concentrated animal feeding operations (CAFOs) contain high strength waste streams from large numbers of closely reared animals that contain significant amounts of nitrogen, phosphorus, and organics. Hog farming CAFOs produce relatively consistent waste streams because these operations are in confined buildings. The current dominant practice for swine wastewater management is a combined conventional activated sludge (CAS) and anaerobic digestion (AD) platform. The standard CAS and AD platform requires a large energy input for aeration and does not include nutrient or volatile fatty acid (VFA) recovery. Recent research has shown potential for treatment of swine wastewater using an anaerobic membrane bioreactor (An-MBR) platform which allows for the capture of biogas, VFAs, nitrogen, and phosphorus. An An-MBR system couples anaerobic digestion and membrane separation to allow for long solids retention times in a small footprint and is capable of producing high quality effluent for discharge. An-MBR systems allow for high carbon conversion and recovery of fermentation products. Existing work in this domain has focused on evaluation and optimization of singular unit processes in isolation. A holistic systems approach to evaluating the environmental and economic performance of the An-MBR platform is needed to guide research and development and provide quantitative comparisons of the system to traditional treatment methods.

This work presents an optimization-based decision-making framework for the evaluation of economic and environmental impacts of the treatment of swine wastewater in an integrated resource recovery system. A process-based model of unit operations which included an An-MBR, VFA recovery, phosphorus recovery through coagulation and flocculation, nitrogen recovery through adsorption, and a final wetland polishing step was first created. These detailed first principles-based models allow for evaluation of a wide problem space rather than ad-hoc consideration of candidate treatment trains. Optimization for the mixed integer nonlinear programing (MINLP) problem is conducted in Pyomo using the IPOPT algorithm. The integrated process models were utilized to perform detailed life cycle assessment (LCA) and technoeconomic analysis (TEA) of the An-MBR system. Preliminary results show that the An-MBR platform is comparable in cost to CAS and AD treatment on an economic basis through value of captured nutrient products offsetting high capex costs of the An-MBR system. An evaluation of the return on energy investment of the isolated An-MBR system showed for typical swine wastewater return on energy investment was approximately 1.4, which is comparable to biodiesel. VFA separations by distillation have been identified as a key source of environmental impacts in the LCA. Detailed sensitivity analysis has been performed around key variables including energy for membrane cleaning, ambient temperature, removal of carbonate alkalinity from the system prior to phosphorus treatment, and the specific composition of the swine wastewater to quantify their impact on LCA and TEA results. The implications of the findings and challenges for developing circular economy solutions for wastewater streams will be discussed.

Exploring the Economics of Urban Water: Valuation, Recycling, and Sustainability

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wednesday, 5th July - 11:30: Water 2 (B0.16 KOG)

Carlos López-Morales [1]

1. *El Colegio de México*

Global trends on population, urbanization, and localization of economic activities suggest that the global economy increasingly becomes urbanized, both in so-called developed and developing countries. A highlight of this process is that the dynamic interactions among metropolitan zones, medium cities, small cities, and rural locations are becoming increasingly complex and intertwined. One of the most outstanding features of this complexity, and one receiving small attention so far in disciplinary literatures, has to do with the way in which these economic entities appropriate water as an essential material input. In other words, the degree to which hydrologic cycles are intervened is dependent on the urbanization process occurring in local watersheds. This paper explores the conceptual and theoretical understanding of the economics of water as an essential economic and ecological input for both social activity and ecological sustainability in the context of the urbanization process. The premise of this exercise is that economic models at different scales (national, regional, or local) should be capable of capturing the fundamentals of water's appropriation at different degrees or urbanization, so as to be able to assess alternative solutions to unsustainable situations. This paper develops a conceptual model of an urban economy embedded in a highly urbanized water basin with the aim of exploring the interdependencies among hydrologic sustainability, competing economic uses, and the generation, treatment and reuse of wastewater under alternative scenarios of water availability. The findings highlight the important roles of treatment technologies, water infrastructure, and administrative arrangements as the foundation for a functioning governance adequate for water sustainability

Towards Water Resource Recovery Facilities: An Integrated System Assessment of Emerging Sewage Sludge Management Technologies in Sweden

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Transitions (short presentations) (B0.41 KOG)

Wednesday, 5th July - 11:45: Water 2 (B0.16 KOG)

Harry Tibbetts [1], *Lara Carvalho* [2], *Jiechen Wu* [1], *Sebastian Schwede* [2], *Ali Ahmad Shahnawazi* [2]
1. KTH Royal Institute of Technology, 2. Mälardalen University

Municipal sewage sludge (MSS) management varies widely between countries and legislative regimes. Within the European directive for sewage treatment France applies over half of MSS to arable land, while The Netherlands has banned the practice (Kelessidis et al, 2012). In Sweden, 34% of MSS is applied to agricultural lands; despite this, official government reports recommend banning the practice over pollution concerns, alongside the most common alternative of land reclamation (Ekane et al, 2020). This is the result of two decades of disagreement, complicated by dual perceptions of MSS as a valuable resource to be returned to the ecocycle vs an unsanitary waste product requiring careful disposal (Ekman Burgman, 2022).
Previous studies have analyzed novel treatment technologies including multiple forms of phosphorus and nitrogen extraction from various stages of MSS treatment, but holistic system analyses are scarce (Bagheri et al 2023). Based on literature review and emerging technologies in Sweden, hydrothermal carbonisation (HTC) is identified as a keystone technology, and can be supported by secondary treatment via nitrogen stripping and phosphorus extraction from liquid and ash waste streams respectively. HTC is an anaerobic thermal treatment of wet organic waste resulting in solid hydrochar and liquid process water products. To address the lack of holistic assessments, an environmental and techno-economic assessment framework (ETEA) is applied to model three MSS treatment scenarios. Each scenario models treatment of MSS by anaerobic digestion (AD) and mechanical dewatering of digested sludge followed by:

- REF: A reference case of storage and arable land application of dewatered digested sludge (DDS)
- ALT1: DDS treatment by Oxypower HTC with Aqua2N nitrogen recovery from process and reject water.
- ALT2: The treatment described by ALT1, followed by hydrochar mono-incineration and Ash2Phos phosphorus extraction.

ETEA is conducted in four stages using data collected from literature and public and private partners. Qualitative and quantitative process flow mapping defines the scenarios and models material and energy flows through the systems. An attributional comparative life cycle analysis (LCA) alongside techno-economic analysis (TEA) follows. The LCA has a gate to grave scope with a functional unit of one ton of total solids treated. Finally, results are evaluated using sensitivity and data uncertainty analysis to identify hotspots and knowledge gaps in the system. Experimental work conducted in tandem with modeling demonstrates a 15% increase in biogas production by applying HTC byproducts to AD to promote biogas production.
Results combining alternative scenarios based on current trends show the potential of emerging technologies to multiply WWTP nitrogen and phosphorus recovery by five and two times respectively, while simultaneously improving net energy recovery by three times. LCA results show reductions of greenhouse gas (GHG) emissions by between 60-70%. Considering emerging MSS technologies from a systems perspective provides critical context that can improve their economic viability. Combining intelligent systems design with these technologies, the models demonstrate how future MSS treatment can provide both good sanitation and recovery of nutrient

and energy resources. Integration of these systems will accelerate the transition from wastewater treatment plants (WWTP) to water resource recovery facilities (WRRF).

Enabling implementation of novel circular water solutions in the coal mine sector

Wednesday, 5th July - 12:00: Water 2 (B0.16 KOG)

***Dimitrios Xevgenos* [1], *Kallirroi Panteleaki* [2], *Maria Mortou* [2], *Krzysztof Mitko* [3], *Marian Turek* [3], *Danai Stroutza* [4], *Mark van Loosdrecht* [4]**

1. Delft University of Technology, 2. SEALEAU BV, 3. Silesian University of Technology, 4. Technical University Delft

Coal is causing environmental degradation not only through the GHG emissions emitted when it is burned, but also during its production phase, with a high environmental cost at local and regional levels through wastewater discharges. The exploitation of hard coal mines leads to the generation of vast amounts of salty wastewater effluents (brines) which have severe environmental impacts. In Poland, the total mine water discharge in the Upper Silesian Coal Basin (USCB) is around 350,000 m^3/day, with the amount of chlorides and sulphates discharged to the rivers being approximately 4,000 tons/day. Brines from these mines are typically discharged into tributaries of the upper Wisła (Vistula) and upper Odra (Oder) rivers causing environmental and economic impacts.

Business modelling combined with resource efficiency and circular economy comprises a recent body of knowledge, that is still in the conceptualization stage (Diaz-Lopez et al, 2019). These fields, often referred to as Circular Economy Business Modelling (CBM) and Sustainable Business Model Innovation (SBMI), are rooted in the wider Business Model (BM) field which has its origins in the 1970s. Although a consolidated research field, BM has an intrinsic difficulty – it aspires to connect, what Pieroni et al (2019) describe as, two "conflicting" domains of knowledge, namely the technical/physical sciences (based on "hard" facts) and the social/economic sciences (based on uncertain assumptions). These challenges can only become more pronounced in the CBM field, where the extant literature is fragmented and comes up only with implementation barriers derived from theory (Evans et al, 2017), with in-depth practical research being largely underexplored (Diaz-Lopez et al, 2019). This is referred to as the "design-implementation" gap by Geissdoerfer et al (2018) who argue that CBMs are rarely implemented in the market, and they fail.

Our work is focusing on addressing the challenge of circular economy implementation by developing a conceptual model that can enable researchers and practicioners conceptualize, design, communicate and implement novel circular economy (business models) solutions, within the (waste)water treatment field. To develop this model we applied a case study research methodology, where we investigated two coal mines in Poland. Through these studies, we showed the importance of determining what we coin as "Circular Water Value" in the coal mine context and how this can be captured from a novel treatment technique that was demonstrated by the authors within the EU-funded project called ZERO BRINE. This research contributes not only on a theoretical level, but also on a practical level. It provides insights to policy makers for the implementation of the Just Transition Fund for the case of Poland, which can be replicated elsewhere within or outside Europe. Currently, this is further being investigated by the authors, involving all the coal mine industries operating these mines.

Can we design urban agriculture without contradicting the water framework directive?

Wednesday, 5th July - 12:15: Water 2 (B0.16 KOG)

***Cristina Madrid-López* [1], *Susana Toboso* [2], *Sergi Ventura* [1], *Joan GIlabert* [3], *gara villalba* [1]**

***1.** Universitat Autònoma de Barcelona (UAB, **2.** Universitat Autònoma de Barcelona, **3.** , Institute Cartographic and Geological of Catalonia (ICGC)*

If not properly planned, urban and peri-urban agriculture can result in increasing pressures over water resources, such as aquifer depletion or nitrate pollution which impact their ecological status. As cities start promoting local agriculture, it is important to provide policy makers with tools to determine the impacts of food production on water resources, from a geo-referenced, systemic water-energy-food perspective.

In this study, we argue that for this activity to happen in a more sustainable manner, urban development must be aware of and influence the drivers and impacts of water use. We assessed the water metabolism of periurban agriculture development in the Metropolitan region of Barcelona (AMB) for a baseline scenario in 2015 and three scenarios of urban agriculture expansion envisioned by the Urban Master Plan: tendential (reducing agriculture), increased agriculture and potential. We analyze irrigation driven by crop production and the resulting water extraction and checked these against a new indicator of river basin vulnerability based on an indicator of ecological status to identify social and environmental hotspots.

We found that UA crop production (69 thousand tonnes, 2015) in AMB is responsible for a water extraction of 30 hm3 from sub basins which mostly have a bad ecological status as reported by the government of Spain. This amount is about 80% blue water extraction resulting from irrigation and associated losses. From all scenario, the one furthest from the current situation is the potential scenario S3, which has an increased water extraction of 70 hm3 for a crop production of 127 thousand tones. Irrigation requirements range between 100 and 700 mm in average in different farms studied and total extraction ranged between 1000 and 8000 cubic meter per hectare in the river basins. The area of farms with bad ecological status and increased water use grows in the increased and potential scenarios.

To support policy -making, we classified crops according to their efficiency and adaptation to climte change. Mandarins and pumpkin are less efficient in terms of water/production and more susceptible to climate change whereas olives and cherries could adapt better. For these cases, agriculture might not be good in providing crops but it might be worth maintaining for other purposes. A second group of crops has average efficiencies. This includes non-citrus fruits like nectarines, apricots and vineyards. Finally, the group of crops that could be considered more efficient and adaptable to climate change includes carob, almonds and herbaceous crops as well as fodder crops like rapeseed and vetch.

Poster Session 1

The Missing Stock: Exploring Concrete Use in Trondheim's Residential Building Foundations

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Pablo Ilgemann** [1], **Tomer Fishman** [1], **Benjamin Sprecher** [2], **Daniel B. Müller** [3], **Jonna Ljunge** [3]*

***1.** Leiden University, CML, **2.** Technical University Delft, Faculty of Industrial Design Engineering, **3.** NTNU, Department of Energy and Process Engineering*

Concrete is one of the most widely used materials in residential building construction. It contributes about 4% to 7% of global greenhouse gas emissions annually. Thus, better understanding the material stocks and flows of concrete can support efforts to better manage this resource and its use. Concrete is especially popular for the construction of building foundations. Previous research has shown that foundations can account for 25% to 60% of residential housing mass. Despite this, no in-depth analysis of material requirements of foundations has been conducted. Foundation design depends on the housing type and soil type. Considering foundations' substantial share of building mass, I analyze them in this thesis in the form of a case study of residential housing built in Trondheim between 2010 and 2020. To account for all emissions from cradle-to-construction site I also compare the concrete production emissions to the last-leg transport emissions. The residential building foundations' material requirements were estimated with a model I specifically developed for this thesis. 507 000 tonnes of concrete were used from 2010 to 2020 to build residential building foundations in Trondheim. The results show that the concrete production emissions represent 99% and the last-leg transport emissions 1% of the total cradle-to-construction site emissions. The average material intensity coefficient across all buildings in Trondheim is 402 kg of concrete in the foundation per one m^2 useful floor area. I disaggregated the buildings into five types: single family house, semi-detached house, rowhouse, apartment building, assisted & communal living. When disaggregated, the building types' material intensities vary, on average, 8% around 402 kg/m^2 useful floor area. The largest difference being 20% below the mean. As a result, there are no substantial differences of material requirements per m^2 useful floor area between different building types. However, building on peat and bog soils increases the material requirements by 80% compared to all other soil types found in Trondheim. This is due to the low bearing capacity of peat and bog soils. Trondheim currently plans its residential zoning until 2034. 5% of the planned zones are located on peat and bog. A rough estimate suggests that up to 380 000 tonnes of carbon could be stored in the affected peat and bog areas, which could be released as construction on this land begins. Together with the 80% increased material requirements of foundations on peat and bog, this can cause a lot of emissions. As a result, my short-term recommendation is that these areas are either preserved as nature reserves or only light structures that do not need a foundation are constructed. In the long-term I recommend that new zoning types for city planning are developed that take soil types into account. Lastly, the effects of soil types should be taken into account in future studies of the material stock in residential housing.

CEEG, an energy efficiency grade dataset for white goods in mainland China at regional and household levels

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Chunyan Wang [1]***, Yi Liu*** [1]***, Zonghan Li*** [1]

1. *Tsinghua University*

White goods (WGs), including washing machines, room air conditioners, water heaters, etc., are large, important and popular household appliances that account for approximately 40% of noncooking household electricity consumption. To improve energy-saving management, the energy efficiency grade (EEG), an integer between 1 (high level, more energy-efficient) and 5 (low level, less energy-efficient), was introduced by the Chinese government in the 2000s and implemented on white goods in early stages. However, due to the lack of actual statistics, it is still not clear how effective the promotion of high EEG WGs has been in China.

Within these contexts, the **C**hina **E**nergy **E**fficiency **G**rade (CEEG) dataset for white goods is developed in this study. The dataset provides average EEG data from both regional and household perspectives. It contains 5 kinds of WGs, including impeller washing machines (IWM), drum washing machines (DWM), electrical water heaters (EWH), room air conditioners (AC), and variable-speed room air conditioners (VAC), which account for 78% of WG-related electricity consumption in China. The regional part contains sales information for the 5 kinds of WGs and the average EEG weighted by sales data for 30 provinces in mainland China (except for Tibet) from 2012 to 2019 by web crawling, retrieving and processing in SQL. The household part comprises household socioeconomic, demographic, living and EEG-related information of 1327 households in Haidian district, Beijing, China, in 2019 and 2021. Due to the tedious process of raw data acquisition and processing, we also deploy traditional econometric methods and machine learning algorithms to predict the annual average EEG of the purchased WGs based on socioeconomic information at different scales and provide the prediction results.

By providing EEG-related data and prediction models at different spatial scales, the CEEG dataset will facilitate the advancement of research on household energy consumption, household appliance consumer choice, and the assessment of energy-efficiency-related policies.

An economic approach to material criticality assessment

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Karan Bhuwalka [1], ***John Ryter*** [2], ***Elsa Olivetti*** [1], ***Richard Roth*** [1]

1. Massachusetts Institute of Technology, 2. United States Geological Survey

Criticality assessments are often used to quantify risks in materials supply chains and the vulnerability of stakeholders to these risks. These assessments are used to create critical material lists that guide industrial and trade policy to protect countries and industries from supply chain disruptions. However, many researchers have pointed out various drawbacks in traditional criticality assessments i) the lack of price feedback and technological growth, ii) issues with aggregating criticality indicators in ways consistent with risk theory, and the iii) lack of temporal dynamics and causal relationships included within criticality analyses. Beyond the criticality literature, economic models of material markets inform resource availability questions in the future by taking econometric, agent-based or systems dynamics modelling approaches. However, due to the details required to build these models, they cannot comprehensively include many factors influencing criticality such as geologic concentration and geopolitical issues. Research has begun to incorporate interconnections between criticality and market variables such as price volatility. Price responses capture how markets react to disruptions: when prices increase sharply in response to supply disruptions, stakeholders are vulnerable to an increase in costs and face risks to their operations.

We present a new methodology that connects criticality assessments with economic models of resource availability. We use expert solicitation along with materials concentration data to capture the first axis of criticality i.e. supply risk or the likelihood of supply disruption. We capture the second axis of criticality i.e. vulnerability to supply risks by building a market model that quantifies the impact of supply disruption (geopolitical tensions, natural hazards, conflict etc.) on materials costs and industry profitability. Through this market model, we are able to demonstrate quantitatively how strategies such as increasing materials substitution can reduce vulnerability to supply disruptions. Finally, we are also able to how environmental policies can impact materials availability.

We use real-world data on mining projects to apply this model to Lithium supply and demand which is used to study the impact of disruptions in lithium supply on battery (and EV) prices. For example, we find that in a baseline scenario for Lithium, a 10% supply disruption is likely and could lead to a 2x increase in materials costs for EV batteries (high vulnerability to supply risk). However, in a scenario with increased materials substitution and technological improvements in mining, the increase in costs is less than 15%. In linking criticality analyses with economic modelling, we provide actionable insights for policymakers. We can evaluate how specific policies (such as diversifying supply chains and increasing recycling) can reduce the impact of supply disruption on critical industries.

Unraveling economic-environmental nexus in China's petrochemical industry towards carbon peaking

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Yingjie Liu* [1], *Hanbo Gao* [2], *Jinping Tian* [2], *Lyujun Chen* [2]**

1. Tsinghua University, 2. School of environment, Tsinghua University

Increasing CO_2 levels have been exerting an irreversible impact on the world average temperature, causing more extreme weather events. China has pledged the well-known "30-60" commitment which requests to peak carbon emissions by 2030 and fulfill carbon neutrality by 2060. It is critical to synergize the reduction of pollution and carbon emissions in China's manufacturing industries towards "30-60" pledge. As one of the most energy and carbon intensive sectors occupying 10.2% of the national total industrial carbon emissions, petrochemical industry plays a significant role in China's economy, where petroleum products are widely used and strenuous to replace.

Petrochemical industry has a long production chain and relies on oil refining & processing as well as raw oil cracking to generate various types of primary chemical materials and further produce synthetic products. Consequently, petrochemical firms customarily gather together in a tract of land to form industrial parks incorporating synergies and industrial symbiosis. This study aims at establishing an industry-infrastructure integrated petrochemical carbon peaking (IIPCP) model to find the most appropriate emission reduction strategy without affecting economic growth for the petrochemical industrial parks. Embedding bottom-up constraints on the areas of land, the requirement of productivity growth, as well as the carbon and pollution reduction goals, the IIPCP model incorporates the high-resolution four-digit level petrochemical industries to identify the key points in various energy and material fluxes between different industries to optimize the systematic synergy. Then, we select the leading typical petrochemical park in China, Shanghai Chemical Industrial Park (SCIP) with collected firm-level data to validate the model effectiveness. Further including multiple promising future development scenarios, the IIPCP model could effectually propose customized implications for the global manifold increasing petrochemical parks.

Infrastructure and the leading oil refinery enterprise Secco in SCIP with relatively steady emission structure have a total of 13.3 million tons of carbon emissions. As for the other manufacturing companies, it can be found that the removal efficiencies of four common pollutants (SO_2, NO_x, PM and VOCs) have reached a high level in the early 13th Five-Year Plan, and later they showed a stable fluctuation trend, so the future emissions of air pollutants will be more fixed and difficult to continue to reduce. In the BAU scenario, the land development rate of SCIP at the end of 2025 will reach 52% (9.35 km^2). Under the principle of "continuously increasing carbon productivity", the total output value of the park in 2025 will be up to 81.8 (stock industries) +82.7 (incremental industries) billion yuan. The corresponding embodied carbon emissions will reach 5.4 and 5.5 million tonnes of CO_2. With 5.74 million tons of carbon emissions (excluding Secco and public utilities) in 2019 as the model constraint, industrial structure optimization is carried out in 2030 to achieve the target of carbon peak. The average carbon productivity of the park can rise from 13,000 yuan/ton of CO2 to 89,000 yuan/ton of CO2, a six-fold increase. Accordingly, In order to achieve the carbon peak target, the expansion of 2614 organic chemical raw materials manufacturing, 2619 other basic chemical raw materials manufacturing and 2653 synthetic fiber mono (polymerization) system manufacturing should be limited. At the same time, the park should expand the scale of 2641 coating manufacturing, 2651 primary form plastic and synthetic resin manufacturing, 2661 chemical reagents and additives manufacturing and 2669 other special chemicals manufacturing industries.

Socio-ecological contagion in urban metabolism

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Thomas Elliot [1], ***Annie Levasseur*** [1]

1. *École de technologie supérieure*

Materials and energy consumed by urban systems are one of the main sources of greenhouse gas emissions. Measuring these flows and their associated emissions is necessary to estimate the impact of cities on climate change in the future. In this research we developed a dynamic model for measuring the carbon footprint of cities' urban metabolism using an integrated socio-ecological systems approach. Illustrated with a case study in Montreal we modelled the urban carbon footprint between 2000 and 2018, and simulated on to 2030 under four scenarios: baseline, increasing adoption of plant-based diets (PBD), pavement/road material circularity (PMC), and a combined approach of the latter two. Results focus on the PBD scenario, which uses the concept of "socio-ecological contagion". This is achieved using a population dynamics model between two groups characterised by a distinct food regime: omnivores and vegans. The greenhouse gas emissions of each food regime is used to estimate the city's changing carbon "foodprint" as the food regimes shift via socio-ecological contagion. The main finding is that the urban carbon foodprint can be reduced significantly with widespread adoption of plant-based diets, but that the foodprint reaches a minimum at 1.97 tonnes CO_2-equivalent per capita. This demonstrates the need to embed food demand in urban climate governance such as nudging towards plant-based food alternatives.

FootprintLab: Putting Footprints to Work

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tim Baynes [1]***, Janet Salem*** [2]

1. Australian National University, 2. The University of Sydney

There is a strong drive from the finance industry, and regulation, for more rigorous, transparent and reliable carbon accounting. The 380 members of the Partnership for Carbon Accounting Financials (PCAF) manage assets and investments in excess of $US90 Trillion and they are setting their own target for reporting Scope 3 GHG emissions by 2026.

The longevity of investments, loans and other financial products means that the finance sector seeks quality information for decisions now, in order to mitigate climate-related risk over the lifetime of their investments. Climate risk as investment risk in the finance sector manifests in:

- Physical risk — exposure to extreme weather, ecological impacts, gradual and extreme
- Transition Risk — policy or technology change, and social responses
- Liability Risk — failure to mitigate, adapt or disclose

The latter two of these relate more to the response to climate change: the climate transition and global decarbonization trend, where investments may be exposed to changing expectations of shareholders, markets and government.

There's a growing carbon information market and this can connect the governance and reporting requirements of finance, with pragmatic needs of business. However, data for research and scientists is different, and used differently, compared with data used by the market. How to translate academic techniques to applications?

FootprintLab has been founded by two long-time members of ISIE with the intent to take the data, the rigor and the transparency demanded by industrial ecology research, and make it broadly available for commercial application. FootprintLab is a for-profit social enterprise that returns revenue to the research institutions who maintain the global environmentally extended Multi-Regional Input-Output models (MRIO) that are the main sources of data.

Our initial surveys of the market have found preferences for data reliability, currency and ease of use. At the same time commercial users ask for greater detail or granularity in data, they also recognize that sufficient accuracy may be enough to make a decision.

Ideally these requirements would be served by a globally complete data set of companies and their products, and their respective carbon intensity relating to purchases or activity using those products. Such an ideal does not yet exist though there may be a possibility of leveraging incoming technology such as digital trade, IOT, fintech, machine learning and artificial intelligence to create reliable, dynamic data sets.

In the meantime, globally, there are a limited number of data resources that connect monetary flows with environmental impact (through MRIO models), for example: EORA, WIOD, EXIOBASE, the GTAP-based OpenEU and GLORIA. Although broadly consistent at a macro-economic level, they differ in features at the level of commercial interest. Another part of FootprintLab's purpose is to improve 'carbon literacy' in the carbon data consumer: to deliver credible numbers and also information on data provenance, measures of accuracy, and appropriate use.

We believe standards of (financial) governance should be accompanied with standards of data provenance, validity and application to carbon accounting. Then the burgeoning carbon information market can present useful (credible and transparent) information for spending and investment decisions.

STiCH: Sustainability Tools in Cultural Heritage

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Matthew Eckelman [1]***, Sarah Nunberg*** [2]

1. *Northeastern University,* ***2.*** *Independent Conservator*

The cultural heritage community—made up of professionals in museums, collections preservation and storage, and archaeological sites—has become keenly interested in environmental sustainability for their field. There have been specific calls for evidence-backed guidance and quantitative environmental comparisons of common choices that they have in their practices, to help fill gaps in their sustainability efforts and programs. There are variety of activities in the field of cultural heritage, that have environmental impact including: the use of hazardous chemicals for art conservation and treatment, object storage and transport, and museum building operations under strict environmental tolerances. While the significance of preserving and maintaining cultural heritage remains difficult to quantify, the use of LCA may inform changes in practices or operational improvements that can reduce the environmental impact of this sector.

We represent a collaboration of environmental engineers and cultural heritage professionals that has been using LCA to improve environmental performance in the sector for nearly a decade. With support from the US National Endowment for the Humanities, we have led the creation of a customized, sector-specific embodied carbon calculator, a library of LCA case studies, and information sheets on pressing sustainability topics. Case studies have included an in-depth analysis of museum loans, comparing material options for mounting and storing paintings, hazard investigation and exposure assessment of common solvents and chemical treatment systems, and evaluation options for applying anoxic conditions. The case studies present alternative designs and materials can reduce environmental impacts substantially.

Together these efforts make up the Sustainability Tools in Cultural Heritage (STiCH) project, which provides guidance and increase ease of access and use of data for those professionals looking to include environmental sustainability as a factor in their decision-making. The site has received nearly 40,000 hits since its launch in collaboration with the Foundation for Advancement in Conservation.

A new IE textbook: Industrial Ecology and Sustainability

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Matthew Eckelman [1], *Thomas Graedel* [2]
1. Northeastern University, 2. Yale University

A new textbook that covers the entire scope of industrial ecology, targeted to advanced undergraduate and beginning graduate students.

Setting the Stage

Humanity, Technology, and Sustainability
The Linked Systems of Human Society and Industrial Ecology
Living Within the Limits of Natural Systems
Industrial Ecology and Sustainability Science Concepts
Organisms, Biological and Industrial
Ecosystems, Biological and Industrial

The Methodology of Industrial Ecology

Providing Services to Society: In-use stocks
Material Flow Analysis
Material Recycling and Reuse
Systems Analysis in Industrial Ecology
Introduction to Life Cycle Assessment
Life Cycle Assessment in Practice
Economics Tools: TEA, Life Cycle Costing, and Economic Valuation
Network Analysis
Data Science in Industrial Ecology

The Resources of Modern Technology

Modern Technology's Resources
The Industrial Ecology of Metals
The Industrial Ecology of Plastics
The Industrial Ecology of Food
The Industrial Ecology of Biomass Materials
The Industrial Ecology of Construction Minerals
Industrial Ecology and Energy
Materials Criticality

Industrial Ecology in Industry

Sustainable Design Frameworks: Design for Environment, Cradle-to-Cradle, Principles of Green Chemistry & Green Engineering
Extended Producer Responsibility, Product Take-Back, and Remanufacturing
Corporate Sustainability

Industrial Ecology of Socio-Technical Systems

Telecoupling in Industrial Ecology
Islands: Geographically-Constrained Systems
Holarchic Industrial Ecology
Industrial Symbiosis
Industrial Ecology and Health Care

Life cycle assessment of a common healthcare procedure - direct laryngoscopy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Grace Filley [1]***, Matthew Eckelman*** [1]***, Jodi Sherman*** [2]

1. Northeastern University, 2. Yale University

The healthcare sector is responsible for approximately 5% of global GHG emissions, as well as pollutants that harm ecosystems and human health. In recognition of this burden, healthcare systems around the world are setting aggressive decarbonization targets and implementing improvements and innovations throughout clinical care. One important area of opportunity is the proliferation of single-use devices and associated solid waste. Often these devised are use in a way that greatly exceeds antisepsis safety standards. Direct laryngoscopy surgery (DLS) involves instrumentation of non-sterile mucosal surfaces with equipment that is routinely subjected to resource-intensive sterilization when only high-level disinfection would be sufficient. There are options to safely reduce material consumption and substitute clean, non-sterile equipment that are less environmentally impactful. We performed cradle-to-grave life cycle assessment of DLS, including global warming potential (GWP), water consumption, and fine particulate matter formation. Three alternative scenarios were modeled: disinfecting surgical tools using high-level disinfection rather than steam sterilization, substituting non-sterile gloves and gowns for sterile ones, and reducing surgical towel and drape sizes by 30%. Changes in disinfection practices would decrease procedure GWP by 11% in each environmental impact category. Substituting non-sterile gowns and gloves reduced the GWP by 15%, with nominal changes to water consumption. Linen size reduction resulted in 28% less procedure-related water consumption. Together, a nearly 30% reduction across all environmental impact categories could be achieved. Adhering to minimum decontamination standards and optimizing non-sterile materials have potential to dramatically reduce healthcare-associated emissions without compromising safety, thereby minimizing the negative consequences of hospital operations to environmental and human health.

Beyond the Industrial Ecology Metaphor – A Complexity Research Agenda for Metabolism Changes

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Charis Luedtke [1], ***Fenna Blomsma*** [1], ***Timothy M. Lenton*** [2]

1. University of Hamburg, 2. Global Systems Institute, University of Exeter

Circular Economy (CE) proposes an alternative approach to the predominant linear economic system and is recognised as an opportunity to a more sustainable future. Previous research has shown that the industrial metabolism of a CE consists of resource- (i.e. Bakker et al., 2014; Graedel et al., 2019), energy- (i.e. Allwood et al., 2011), information- (i.e. Kristoffersen et al., 2020) and value-flows (i.e., Bocken et al., 2016), combined with the accompanying infrastructure and technology (Blomsma et. al., 2022). However, at present, little guidance exists as to *how* these flows can be turned into a coherent whole and what a robust circular metabolism looks like that fits within planetary boundaries. This hinders the design and implementation of circular systems, as tools and methods to scan and identify improvement opportunities within circular value chains are lacking.

Industrial Ecology (IE), also referred to as "the science of the circular economy" (Graedel, 2015), has been and remains important for the development of conceptualising and developing tools and methods to operationalise the idea of a sustainable CE. The field of IE uses the natural ecosystem as a model for the development and organisation of industrial systems by considering the natural ecosystem as a metaphor for the industrial one. This has facilitated the study of many analogies between the two ecosystems. However, to date, the field has not placed sufficient emphasis on the natural laws and principles governing changes that bring forth new and more complex metabolic systems. During these changes, resource-, energy-, and information-flows tend to reconfigure as a whole and new forms of complexity emerge (Christian, 2011; Spier, 2015).

Whilst both natural laws and principles (Graedel, 1995; Isenmann, 2008; Spiegelman, 2008) as well as complexity (i.e. Dijkema & Basson, 2009; Meerow & Newell, 2015; Rotmans & Loorbach, 2009) have received attention within the field of IE, their intersection remains under-studied. It is here, however, where insights could be generated with regards to how essential flows - their origins, their connections and their interactions - can lead to new stable and sustainable metabolic configurations. From this, important characteristics of robust and sustainable circular systems can be derived and this knowledge can be used to make recommendations for the improvement of, for example, circular value chains. This in turn closes the gap between the idea of a CE and action taken to implement it and enables agency in the face of complex changes.

This paper brings together work from other disciplines that can be used to shed light on large scale metabolism changes, e.g. from complexity science (i.e. Rifkin, 2011; Spier, 2011; Smil, 2017) as well as earth system science (i.e. Lenton & Watson, 2011; Lenton et al., 2016), and synthesises this into a research agenda to advance the field of IE. We start with examining the different uses of the IE metaphor and proceed with a synthesis review based on a transdisciplinary approach. The objective is to formulate a complexity research agenda for large scale metabolism changes that supports the transition to sustainable circular systems.

Developing Mental Skills for Entrepreneurial Resilience: Identifying Best Practices

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Erin Wynn [1], ***Lori Dithurbide*** [2], ***Luke DeCoste*** [1], ***Haorui Wu*** [2], ***Meghann Coleman*** [1], ***Kyle Breen*** [2]

1. MindFrame Connect, 2. Dalhousie University

MindFrame Connect is a national non-profit operating in Canada that seeks to upskill entrepreneurs and their mentors, communities, and services to increase entrepreneurial resilience and performance. Our focus is on strengthening not only the individual entrepreneur, but enhancing the ecosystems they operate within to make entrepreneurship a more supported and sustainable career option for Canadians. Presently, we have undertaken 160 workshops on the topics of entrepreneurial resilience, mentorship, entrepreneurship for underrepresented groups, and program support training, reaching approximately 4000 participants. Our multi-week eCourse has had approximately 130 students, and we have been engaging in regular community needs assessments, including semi-structured open-ended interviews with 150 notable entrepreneurs in Canada and frequent focus groups with government and university entrepreneur support programs.

In the innovation and entrepreneurship sector there has been a growing demand for workplaces, cultures, and programs that allow entrepreneurs to take an integrated approach to their wellbeing. The MindFrame Connect Mental Skills for Entrepreneurial Resilience project defined the concept of entrepreneurial resilience as it related to performance, health and wellbeing, and community supports. As the entrepreneurial journey often contains crises, setbacks, and adversity, an understanding of both the individual and systemic factors that relate to psychological resilience is required to better equip entrepreneurs for stressors they may encounter. The information gathered throughout our project is important to the international entrepreneurial community and those who support their work, as it provides insights into the unique mental skills required by entrepreneurs as well as the role of government, education programs, and broader ecosystems to enhance the experience and retention of potential entrepreneurs in our countries.

Our project has used individual semi-structured open-ended interviews with 150 entrepreneurs in Canada on the topic of mentorship and ecosystem needs, 8 semi-structured in-depth interviews with entrepreneurs on their resilience practices, a mentorship meta-analysis of 276 articles, and our workshop participant data to design and develop program tools and training. Participant data includes demographic information, content relevance and fit, skill building assessment and qualitative feedback. We have approximately 830 survey responses from our workshops and eCourses.

From this data, MindFrame Connect has developed several leading practices to support mental skills for entrepreneurial resilience:

1. The development of effective mentors in the innovation and entrepreneurship space, who are able to support and guide entrepreneurs not only in the tactical business-building skills but also in the mental skills necessary to engage healthily with entrepreneurship;
2. Knowledge translation from fields of organizational and positive psychologies to on-the-ground skill-building sessions and resources for entrepreneurs and the organizations who support them
3. Identification of three foundational mental skills for resilience development in entrepreneurs; self-awareness, growth mindset, and reflection.

The work of MindFrame Connect is funded by the Future Skills Centre (Employment and Social Development Canada) focused on the development of workplace skills that prepare Canadians for jobs of the future.

TEA and LCA of fuels and products from using industrial carbon capture and metabolic engineering

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Anthony Roulier [1], ***Matthew Eckelman*** [1]
1. *Northeastern University*

Metabolic engineering of microorganisms is used extensively in the production of chemicals, pharmaceuticals, and biofuels. We are investigating a new bioprocess train that captures CO2 from ethanol fermentation (conducted at large scales in the Midwest United States and elsewhere) and generates biodiesel in two steps using synergetic strains of yeast. Unlike growing microalgae for biodiesel, this technology does not rely on sunlight and can be implemented in large, enclosed reactors, rather than requiring large amounts of surface area (and typically land) for collecting solar radiation. While the process is being optimized at laboratory scales, we apply prospective techno-economic analysis (TEA) and life cycle assessment (LCA) to explore its potential economic feasibility and environmental efficacy. Process modeling reveals that the viability of the technology is determined in large part by mass transfer rates of the gases into the culture medium (specifically the low solubility of hydrogen gas), the corresponding high gas flow rates required, and the relatively high temperature that the engineered strains need to survive. The choice of buffering solution is also an important determinant of both cost and environmental impacts, prompting the search for potential waste streams that could be used as an industrial symbiosis opportunity. Advanced bioprocess technologies for yeast cultures could potentially lead to substantial improvements in gas transfer rates (and hence CO2 metabolism by the microorganisms and overall process yields) but their life cycle economic and environmental trade-offs remain unknown. This presentation will describe a cutting-edge technology for generating next-generation biofuels and bio-based chemicals and will use TEA and LCA to identify some of the engineering and cost hurdles that we face in our transition to a bio-economy.

Internal climate mitigation requirements for considerations of carbon-neutral infrastructure projects – a roadmap perspective towards net-zero carbon emissions in the construction supply chain

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ida Karlsson [1]

1. Chalmers University of Technology

The construction sector accounts for approximately 25% of global CO_2 emissions [1] and achieving net-zero greenhouse gas (GHG) emissions in the sector before mid-century is thus imperative in reaching the goals of limiting climate change to well below 2°C as set out in the Paris agreement.

Carbon neutrality has become a buzzword in the building and construction sector [2] and already now construction projects are starting to claim being carbon neutral [3]. However, these claims so far involve the use of carbon offsets to achieve carbon neutrality. Credible guidelines, such as the recently introduced ISO Net Zero Guidelines [4] state that an organization should “take full responsibility for reducing Scope 1, Scope 2 and Scope 3 emissions without shifting undue responsibility for GHG emissions to another organization”. With these scopes, the guidelines include direct GHG emissions (Scope 1), indirect GHG emissions (Scope 2) from purchased energy as well as emissions along the value chain (Scope 3), which is the same system boundary used in this study. While the guidelines thus specify that the first step towards carbon neutrality is to cut project emissions, to date there has not been any set requirements as to how much a project needs to reduce associated greenhouse gas emissions within the project supply chain before using carbon offsetting.

In this study, a comprehensive literature review and results from previous studies by the author [5], [6] are combined with plans in industry roadmaps which set out how industries and sectors are to contribute towards the Swedish national goal of reaching net-zero greenhouse gas emissions by 2045 [7]. The result of this review is evaluated, analyzed, and merged towards project requirements for key materials, transports, and construction process inputs across the construction supply chain of transport infrastructure projects. The project requirements have subsequently been vetted with industry experts and adjusted accordingly.

The result of the study is a set of requirements for project carbon mitigation activities and emissions factors for key materials and inputs strengthened along a five-year timeline from 2025 towards 2045. The requirements cover requirements on cement and concrete, steel, asphalt, mass handling, material transports and construction machinery. Some examples of the types of measures that are incorporated in the requirements include cement clinker substitution, the level of binders in concrete, materials efficiency due to structural optimization, recycled content and/or reuse of materials, reuse of excavation masses, transport and construction site logistics optimization, and electrification of trucks and construction machinery. The requirements combine progressively reduced emission factors per materials with material or material component requirements as well as design or management criteria which combine into percental reductions over time. These are intended as a set of general pre-requirements for any project to have fulfilled before any carbon offsetting would be seen as a possibility to achieve carbon neutrality.

While there are also pre-requisites linked to the heavy industry and transport climate transition, the focus of the work is on parameters, conditions, and activities over which a specific project supply chain has control. Overall, we find that with the combination of industry and project mitigation measures for transport infrastructure at a national level has the potential to contribute to GHG emissions reduction of 34% to 2025, 74% to 2030 up to reductions of 97% to 2045 compared to a 2020 baseline.

Towards ecological sustainability: A cultural ecosystem service pathway in regenerating Philippines' urban green infrastructure

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Brian Chiu [1], ***Eugene Mohareb*** [2]

1. University of Santo Tomas, 2. University of Reading

Urban green spaces are an important part of our cities, and they play a vital role not only in promoting the health and wellbeing of people but also in connecting people to nature and its benefits. The sustainable management of urban green spaces faces a number of challenges such as the decline in biodiversity due to habitat fragmentation and degradation, the negative effects of climate change on cultural resources, and the negative effects of human interactions on urban green spaces. These problems threaten the long-term stability of urban green infrastructure. The ecosystem services framework provides a means to assess the value of various regulating, supporting, provisioning, and cultural services towards a more sustainable resource management. This framework has often been applied to urban green spaces, though the literature on measurement of value of cultural ecosystem services in the urban sphere remains relatively limited.

This research aims to assess the value of cultural ecosystem services of urban parks using a novel framework that combines a visual manifestations approach with structural diversity analysis to determine various interactions between cultural services. The framework was applied to two important urban parks in the National Capital Region in the Philippines, with a population of over 13 million. Urban green space is scarce in Manila, with only 5 square meters per capita, well below the WHO recommendation of 9 square meters per capita. The interactions in the parks were assessed using a systematic observation protocol that allowed the identification of different uses within the park and linked it to a specific green and grey component. We also examined the structural dimensions of the park to understand how they may be linked to interactions among people.

Findings highlight social interactions (35%), walking (17%), and sedentary activities including sitting, standing and observing (12) as the most observed in the two parks. Findings on the structural dimensions of the park, on the one hand, showed that the distribution of activities in the urban parks was found to be mostly concentrated in grey spaces (94%) such as paths, trails and edges (64%), site fixtures (17%), and structures (13%). On the other hand, the structural diversity analysis showed that this tool can be a means to highlight the green and grey space value of the parks in terms of where interactions occur and its capacity to support and deliver the benefits to people.

The findings suggest that implementing a cultural ecosystem service approach in the regeneration of urban green sites (e.g. urban parks and ecological parks) provides important data towards a pathway to ecological transformation of the Philippines' urban green space systems. The conceptual framework developed for this study, which centered on visual manifestations to highlight interactions between individuals and their surroundings, created a link to build ways for capturing these values for management and decision-making. Additionally, the park's green and gray dimensions also played a key role in defining the spaces of interaction and their associated value in terms of its capacity to deliver the important cultural ecosystem service benefits.

A life cycle sustainability assessment of the miracle tree's leaf powder and seed oil

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Moringa oleifera (MO), also known as the "miracle tree," is highly multifunctional, with leaves used in nutritional supplements, fertilizers, and animal feeds. Its seeds are rich in oil content, and MO seed oil is used in cosmetic products, cooking, and biodiesel. A coproduct of MO seed oil extraction is the seedcake, which has a high protein content and is effective in water treatment. Although widely promoted for rural livelihood improvement in the Global South, the environmental, social, and economic impacts of MO production remain unexplored, and there is a need for a holistic sustainability assessment of MO.

Accordingly, this research adopts a life cycle framework to assess the social, economic, and environmental impacts of MO leaf powder and seed oil production. We do so by conducting an environmental life cycle assessment (ELCA), social life cycle assessment (SLCA), and life cycle cost assessment (LCCA) on MO leaf and seed products. The system boundary for each assessment is cradle-to-factory gate. Our study took place in Ghana, where processors source MO leaves and seeds from an outgrower agribusiness scheme. MO leaves and seeds are purchased from smallholder farmers and intermediaries before being processed into their final products. Since MO is grown and processed for income generation, this study used economic value as the functional unit for MO leaf powder and seed oil.

We collected the inventory data for this research by working with four small and medium-sized enterprises involved in MO leaf powder or seed oil production. Fifty-two MO-growing farmers were also interviewed to collect the inventory data necessary for each assessment. The ELCA, SLCA, and LCCA results were compared and integrated to complete the life cycle sustainability assessment. Hotspots for each assessment were identified, and recommendations were made for reducing adverse environmental impacts and improving social and economic benefits accordingly.

The multibillion-dollar global trade of MO products is expected to continue to grow in the coming years. Rural communities and businesses in the Global South can have a positive social impact while economically benefiting from accessing export markets for MO. Optimizing multifunctional crop management with life cycle thinking offers a holistic approach to characterizing MO leaf and seed products' sustainability and raises awareness of tradeoffs and synergies among social, economic, and environmental impacts. Our research findings are being used to inform stakeholder decision-making for those engaged in the MO sector. Those interested in other multifunctional crops can also adopt a similar framework to assess their crop's sustainability.

Reconciling regional costs with global benefits: Lithium from Clays

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Venkat Roy [1]***, Sameer Kulkarni*** [1]***, Fu Zhao*** [1]

1. *Purdue University*

A rapidly growing electric vehicle industry aiming to de-carbonize the transportation sector has led to a rush for critical battery materials that power the EVs. With about 8-10 kg required for each EV battery, lithium is one such key material. Currently, most of it is mined in Argentina, Chile, and Australia while China plays a key role in refining lithium. But several new reserves have been identified in the US, Mexico, and many countries across Europe. While these sources can help create a more distributed supply chain, it can also be accompanied with negative consequences to the regions surrounding the mines, such as: transformation of the land, water depletion and pollution, biodiversity loss, and other damages to local ecosystems. In this study we assessed the environmental impacts of extracting lithium from clays in the McDermitt Caldera (Nevada) where most of reserves in the US are located (over 2 Mt of Li with concentrations ranging from 2000 ppm - 6000 ppm). Depending on the extraction method and type of clay, lifecycle GHG emissions of the extraction process range from 6-24 kg CO_2eq per kg Lithium Carbonate Equivalent (LCE). This is small compared to the potential emission reduction from its end-use in an EV battery (<1-3%) but there are other ecological impacts to consider that are more sensitive to location and rate of extraction. For example, direct freshwater requirement is 82 - 96 m_3 per ton of LCE extracted; this implies a single mine with a 60 kt annual production rate (in-pilot stage) can withdraw up to 4 Mgal/day. Additional work is being undertaken to evaluate the spatial distribution of life cycle impacts on categories such as land use, ecotoxicity and water consumption.

Towards Water Resource Recovery Facilities: An Integrated System Assessment of Emerging Sewage Sludge Management Technologies in Sweden

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Transitions (short presentations) (B0.41 KOG)

Wednesday, 5th July - 11:45: Water 2 (B0.16 KOG)

Harry Tibbetts [1], *Lara Carvalho* [2], *Jiechen Wu* [1], *Sebastian Schwede* [2], *Ali Ahmad Shahnawazi* [2]
1. KTH Royal Institute of Technology, 2. Mälardalen University

Municipal sewage sludge (MSS) management varies widely between countries and legislative regimes. Within the European directive for sewage treatment France applies over half of MSS to arable land, while The Netherlands has banned the practice (Kelessidis et al, 2012). In Sweden, 34% of MSS is applied to agricultural lands; despite this, official government reports recommend banning the practice over pollution concerns, alongside the most common alternative of land reclamation (Ekane et al, 2020). This is the result of two decades of disagreement, complicated by dual perceptions of MSS as a valuable resource to be returned to the ecocycle vs an unsanitary waste product requiring careful disposal (Ekman Burgman, 2022).
Previous studies have analyzed novel treatment technologies including multiple forms of phosphorus and nitrogen extraction from various stages of MSS treatment, but holistic system analyses are scarce (Bagheri et al 2023). Based on literature review and emerging technologies in Sweden, hydrothermal carbonisation (HTC) is identified as a keystone technology, and can be supported by secondary treatment via nitrogen stripping and phosphorus extraction from liquid and ash waste streams respectively. HTC is an anaerobic thermal treatment of wet organic waste resulting in solid hydrochar and liquid process water products. To address the lack of holistic assessments, an environmental and techno-economic assessment framework (ETEA) is applied to model three MSS treatment scenarios. Each scenario models treatment of MSS by anaerobic digestion (AD) and mechanical dewatering of digested sludge followed by:

- REF: A reference case of storage and arable land application of dewatered digested sludge (DDS)
- ALT1: DDS treatment by Oxypower HTC with Aqua2N nitrogen recovery from process and reject water.
- ALT2: The treatment described by ALT1, followed by hydrochar mono-incineration and Ash2Phos phosphorus extraction.

ETEA is conducted in four stages using data collected from literature and public and private partners. Qualitative and quantitative process flow mapping defines the scenarios and models material and energy flows through the systems. An attributional comparative life cycle analysis (LCA) alongside techno-economic analysis (TEA) follows. The LCA has a gate to grave scope with a functional unit of one ton of total solids treated. Finally, results are evaluated using sensitivity and data uncertainty analysis to identify hotspots and knowledge gaps in the system. Experimental work conducted in tandem with modeling demonstrates a 15% increase in biogas production by applying HTC byproducts to AD to promote biogas production.
Results combining alternative scenarios based on current trends show the potential of emerging technologies to multiply WWTP nitrogen and phosphorus recovery by five and two times respectively, while simultaneously improving net energy recovery by three times. LCA results show reductions of greenhouse gas (GHG) emissions by between 60-70%. Considering emerging MSS technologies from a systems perspective provides critical context that can improve their economic viability. Combining intelligent systems design with these technologies, the models demonstrate how future MSS treatment can provide both good sanitation and recovery of nutrient

and energy resources. Integration of these systems will accelerate the transition from wastewater treatment plants (WWTP) to water resource recovery facilities (WRRF).

Enabling Shifts Towards Sustainable Circulation of Materials in Transportation Infrastructure: Development and Testing of an Approach Using Systems Thinking

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Scenarios (short presentations) (B0.31 KOG)

Sara Malmgren [1], ***Kristina Lundberg*** [2], ***Rajib Sinha*** [1]

1. KTH Royal Institute of Technology, 2. Ecoloop AB

How could enabling conditions for shifts from linear material flows towards sustainable circulation of materials in Swedish state transportation infrastructure be achieved? And more generally, how could possible paths towards enabling transitions and other shifts be identified, utilizing systems thinking to handle complexity associated with these, building on transition theory and knowledge of actors in the value chain? In a manner adapted to support policy development processes, focussing on identifying priority areas for interventions as well as development of chains of reasoning (as a basis for development of, e.g., impact logics)? This has been explored in this project, designed as a pilot project developing and testing an approach adapted for the purpose. Five semi-structured interviews were performed to collect data on major drivers for increased circulation of materials, system failures (Weber and Rohracher, 2012) impeding realization of sustainable circulation, as well as how system failures could be resolved. Sustainable circulation of materials here refers to circulation i) meeting quality requirements of the technical installation and with respect to its local environment as well as ii) realizing national economically cost effective measures for decreased impacts on climate change. A causal loop diagram describing how shifts towards sustainable circulation could be enabled was assembled building on the idea of Smith et al. (2005) of transition as a result of selection pressures and resources from within and outside of the regime mobilized to meet these. The model was also reformatted to a "transition logics" designed to support dialogue, and the possibility to develop a chain of reasoning based on the results was also demonstrated. Seven interacting main paths towards enabling shifts towards sustainable circulation were identified, including the following suggested priority areas for interventions: 1) digital systems for keeping track of materials including declaration of these as well as supply within a reasonable distance, 2) business models and complementary measures for co-ordination between flows, 3) development of conditions for using material with the right quality given its application, including standards, testing methods and prerequisites for taking decisions based on these, 4) investigating possibilities for development of regulations for decreased administration and equal demands on circulated and primary materials, 5) improved conditions for interpreting regulations, 6) learning related to use of circulated materials and 7) further development of a goals for sustainable circulation of materials in state transport infrastructure, including a description of market failures which need to be targeted. Possible next steps within priority areas for interventions were discussed, as were possible priorities in the near future building on, e.g., the framework for sustainable market transformation previously developed by Nijhof et al. (2022). Also limitations of the approach used in the project were discussed, and possibilities for further development of the approach to provide an improved knowledge basis for policy development striving to enable transitions and other shifts were explored.

Nijhof, A., Wins, A., Argyrou, A. och Chevrollier, N. 2022. Sustainable market transformation: A refined framework for analyzing causal loops in transitions to sustainability. *Environmental Innovation and Societal Transitions* 42(2022): 352–361.

Smith, A., Stirling, A. och Berkhout, F. 2005. The governance of sustainable socio-technical transitions. *Research Policy* 34 (2005): 1491–1510.

Weber, K.M. och Rohracher, H. 2012. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Research Policy* 41(6): 1037-1047.

Establishment of an Online Sustainable and Resilient Circular Economy Laboratory: SRC-Lab

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Devrim Yazan [1]

1. University of Twente

Transition to a sustainable and resilient Circular Economy (CE) requires an acceleration as resource scarcity and depletion represent economic risks and waste overproduction threatens environmental ecosystems and societal wellbeing. Traditional take-make-use-dispose based on a linear economy paradigm is unsustainable, triggers resilience problems, and causes pressure on local and global supply chains, governments, and consumers. Although the Sustainable Development Goals (SDGs) of the United Nations recommend CE transition (CET) as a global priority, a large variety of barriers (e.g., non-circular product development, insufficient renewable energy use, unsustainable consumer behavior, lack of efficient policies) slow down this transition.

As main stakeholders, companies, consumers/citizens, and governments need to cooperatively take action for a successful CET and develop integrated stakeholder engagement. From educational perspective, the future CE awaits its implementers who have diverse backgrounds but complementary skills and a commonly shared vision. However, currently CE education remains underdeveloped and fragmented addressing only field-specific aspects in an isolated manner in various programs. Accordingly, CE education requires an inter- and cross-disciplinary approach which must involve multiple programs from multiple faculties.

To teach students this necessary stakeholder involvement and multidisciplinary cooperation, the development of an online serious game environment supported by challenge-based learning is a perfect fit. In such edutainment and experiential learning environments, students can experience different stakeholder roles to cooperatively tackle sustainability and resilience challenges at micro, meso, and macro levels. This study proposes the establishment of an online "Sustainable and Resilient Circular Economy Laboratory" which contains multiple plug-and-play game modules addressing challenges of the CET.

Embodied emissions from building materials at risk of climate-driven flooding hazards

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Xiaoyang Zhong [1], ***Tomer Fishman*** [2], ***Paul Behrens*** [3]

1. *Leiden University,* ***2.*** *CML Leiden,* ***3.*** *Leiden University, CML*

Climate and land-use changes have driven an increasing risk of extreme flooding events to life and infrastructure. These events may drive large material losses and associated embodied emissions. Here we map building materials at risk of flooding hazards and material-related greenhouse gas (GHG) emissions across 49 European countries under current and future climate-change and land-subsidence. We show that currently 11.7 Gt of building materials, or 11.6% of those in-use, are at risk of a 1-in-100-year flooding event. Expected annual damage (EAD) to building materials, in the absence of flood protections, reaches 329 Mt per year, equivalent to ~109 MtCO2eq per year of embodied GHG emissions. With assumed current flood protection standards fully in place, the current emissions from EAD are reduced by nearly 92% (~100 MtCO2eq, nearly 20% of the current annual building material related emissions in Europe). Emissions see an increase of 71% to 180 MtCO2eq per year in 2080 under a high-emission climate scenario (RCP 8.5). Climate mitigation from RCP 8.5 to RCP 4.5 reduces these embodied emissions by 25 MtCO2eq (14%) to 147 MtCO2eq per year. Overall, we show that climate mitigation and flood protection are crucial in reducing material losses and embodied emissions.

Drivers of fluctuating embodied carbon emissions in international services trade

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jingwen Huo [1]

1. *Tsinghua University*

Service industries are always considered "green" because of the marginal direct emissions although they account for 65% of the world GDP and over 20% of total global trade in 2019. Here, we quantify the evolution of carbon emissions embodied in services trade from 2010-2018 and identify the driving factors of emission change at the global and regional scales. The annual growth rate of embodied emissions exported from the global South (2.0%) is double that of the global North (1.0%), with a different trade structure. We further identify three trade patterns of service export in the global South based on the bilateral trade partnership and annual growth rate. Three kinds of specific emission mitigation policies are proposed based on the characters of services trade and different trade structures between different regions. The results provide quantitative evidence currently lacking and critical to policy decision making.

Plant-level capacity optimization towards socioeconomic efficiency improvement and carbon neutrality in China's cement industry

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Shuntian Xu [1], ***Lei Xu*** [1], ***Xin Tian*** [1]

1. *Beijing Normal University*

Cement is an essential material in infrastructure construction and urbanization. The cement industry is one of the largest sources of CO_2 emissions in China and plays an important role in achieving China's carbon neutrality target. As the world's largest cement producer, China is working to optimize the scale and structure of its cement production capacity, which requires improving the cement industry's production efficiency and low-carbon production technologies, as well as adapting to the changing patterns of socioeconomic demand. On the demand side, this study built a cement dynamic material flow analysis model under population aging at the city level in China from 1990–2060. On the supply side, we considered emission reduction measures such as clinker substitution, carbon capture and sequestration, efficiency improvement, alternative fuel use, and low-carbon cement use. We also considered the carbon sequestration effects of cement. Furthermore, we used data envelopment analysis (DEA) to dynamically evaluate the overcapacity, productivity and factor allocation efficiency of the cement industry in different regions and cities, and carried out simulations of plant-by-plant capacity optimization strategies towards carbon neutrality targets. The results indicate a declining trend in cement consumption with a high degree of uncertainty, where demographic changes play an important role. The carbon neutrality technology pathway depends mainly on capacity regulation policies and is also influenced by consumption demand and use phase behavior. Using Non-dominated Sorting Genetic Algorithm (NSGA) as a multi-objective optimization method, we find that an optimization path that integrates resource endowment, demand distribution, and green energy potential can significantly improve the productivity and factor allocation efficiency of the cement industry while achieving the carbon neutrality goal. Based on DEA efficiency analysis and a comprehensive modeling of the supply-demand chain and carbon sequestration effects, this study draws a detailed and effective capacity optimization roadmap for carbon neutrality in China's cement industry. Our findings offer new perspectives on industrial capacity optimization towards such multiple objectives as socio-economic development and CO_2 reduction.

Bridging Critical Components Recycling Gaps: Comparative life cycle assessment of permanent magnet recycling processes

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Lu Wang [1], ***Peng Wang*** [2], ***Qian-Qian Wang*** [3], ***Shen Zhao*** [4]

1. Ganjiang Innovation Academy, Chinese Academy of Sciences, 2. Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, 3. School of Resource and Architectural Engineering, Gannan University of Science and Technology, 4. Faculty of Materials Metallurgy and Chemistry, Jiangxi University of Science and Technology

Global demand of critical raw materials, mainly driven by critical components like neodymium-Iron-Boron (NdFeB) based permanent magnets, is expected to increase unprecedentedly as the world strives for zero carbon future. Given the primary supply of critical raw materials from virgin ores is risky, costly, and environmental taxing, their recycling from industrial critical components manufacturing waste and End-of-life (EOL) products is crucial and promising. However, the present recycling practices are quite limited, and the detailed environmental analysis of their recycling processes is scarce. By focusing NdFeB permanent magnets, we perform the global first Life Cycle Assessment (LCA) of five available processes covering three commercially practicable approaches (i.e., magnet-to-magnet process, pyrometallurgical and hydrometallurgical processes) plus two emerging processes for NdFeB magnet recycling. We set out to quantify the environmental impact of producing 1 kg of NdFeB magnets using virgin material, compared with producing 1 kg of NdFeB magnets from recycled material. The results indicate that the magnet-to-magnet process has the least environmental impact, followed by the molten salt electrolysis process. The selective leaching process has a lower impact than the complete leaching process, although the difference is minimal. The selective leaching process is more cost-effective and has a shorter treatment time. The double salt precipitation process is a complicated process with a high environmental impact, making it less widely used. Currently, most NdFeB recycling enterprises in China use the selective leaching process. It should be noted that the magnet-to-magnet method requires clean NdFeB waste and that the molten salt electrolysis method is still in the experimental stage and requires specialized equipment and personnel.

Life Cycle Sustainability Management (LCSM) in SMEs – Learnings from electronics in the developing economies

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Sonia Valdivia [1] ***, Adrien Specker*** [1] ***, Salomé Stähli*** [1]

1. *World Resources Forum*

Background and aims. Small and Medium Enterprises (SMEs) play a major role in most economies, particularly in the developing ones (contributing to GDP with over 55% and to job creation with over 65%). This paper aims to identify the social and environmental hotspots in the electronics sector in the emerging regions and assess improvement options. The focus is on SMEs as most actors involved in electronics in these regions are SMEs. They are typically assemblers of imported components e.g. from Asia and not producers of electronics components (e.g. printed circuit boards, transistors, li-ion batteries).

Other features of concerned electronics value chains are the high composition of micro-enterprises and individuals subsisting with the end-of-life management of e-waste (also defined by some legislations as informal workers), the expanded capability and accessibility of expertise for extending the electronics lifespan (e.g., via repairing and refurbishing, software upgrading, etc.) repairing and renovating used electronics to re-enter into the second-hand products market. There is a growing market for used electronics.

Method. Five pilots were conducted in 2021-2022 in Colombia and Peru to investigate the social and environmental hotspots along the life-cycle and improvement measures, namely, LCSM actions. The pilots followed the guidelines provided in the UNEP/WRF Supplement for Electronics (2022) (https://wedocs.unep.org/handle/20.500.11822/41519).

Results. Social hotspots relate to two stakeholder groups: workers (e.g. exposure to chemicals of concern and questionable ergonomic conditions for women in certain conditions) and suppliers upstream and downstream (e.g. poor working conditions if individuals are engaged in subsisting activities). Environmental hotspots relate to impacts on land and water (e.g. from e-waste and packaging due to poorer waste management infrastructures available) and on resource depletion (e.g. of critical raw materials such as lithium and cobalt).

Measures identified and implemented cover improved chemicals management along the value chain by enhancing cooperation with components producers, eco-design of packaging, EPR programs, and new business models for allowing the lifespan extension of electronics.

Life Cycle Assessment (LCA) of a Bio-Fuel Cell Fed with Waste Biomass: Potential for Scale-Up and Process Optimization

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Eleonora Rossi [1]***, Daniele Cespi*** [1]***, Fabrizio Passarini*** [2]***, Irene Maggiore*** [1]***, Leonardo Setti*** [1]

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Turning waste into a valuable resource is globally mainstreamed by approaches and legislations including the circular economy and several SDG goals. However, effective implementation of virtuous waste management strategies often requires innovative and versatile technologies and proven environmental preference over traditional waste treatment and disposal routes. In particular, biowaste is a material stream under investigation because of its potential source for added-value chemicals and renewable energy.

In a past research, a team from the University of Bologna has developed a biofuel cell technology to serve as a treatment for discarded biomass originated from agriculture. This cell aims to valorize biomass by producing electricity and soil conditioner. A main advantage of this cell is that its structure can be self-produced using a 3D printer, a feature that reduces cost and increase versatility in adapting the design as needed. Moreover, the developed fuel cell is portable and can process also relatively small volumes of feedstock so that it can be used on the site where the biomass originated.

In this study, is focused on through the life cycle assessment (LCA) is applied to estimate the environmental performance of the bio-fuel cell developed, with emphasis to understand which stages of the process are the most impactful to the environment and where prioritizing efforts should be dedicated to achieving sustainability improvements.

The results showed that the impacts related to the production of the cell (i.e., infrastructure) are negligible if it is used about 400 times, at least. It was also observed that the greatest impact is due to energy consumption and the usage of phosphoric acid. Environmental benefits, instead, results from the recovery of phosphorus present as H_3PO_4. In addition, further benefits are related to energy recovery and soil conditioner production.

Alternative scenarios were created to test different combinations of acids and bases. The base is used for a hydrolysis reaction during solution preparation and the acid for final neutralization. Nitric acid and potassium hydroxide were used instead of phosphoric acid and sodium hydroxide. KOH's use seems promising because it adds potassium to the nutrient output.

Because of the large portion of impacts due to energy consumption, scenarios based on renewable sources (e.g., solar energy) have been also explored. A further model was also created to check the benefits of heat recovery during the hydrolysis reaction. Finally, all these scenarios were compared with traditional treatments for biomass waste, such as composting and anaerobic digestion. The LCA results demonstrate that the biomass-fueled cell technology is highly promising and competitive but also points to a decrease in energy consumption and nutrient recovery as the main hotspots for further improvements.

Expanding the United Nations Framework Classification for Resources (UNFC) to a National Level: A Swiss Case Study on Embedded Electronics

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Manuele Capelli** [1], **Kirsten Remmen** [1], **Charles Marmy** [1], **Ulrich Kral** [2], **Iman Dorri** [3], **Soraya Heuss-Assbichler** [3], **Patrick Wäger** [1]*

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In order to develop sustainable resource policies and strategies, it is becoming more and more important to include information about the availability and recoverability of secondary raw materials (SRMs), particularly critical raw materials (CRMs), in national inventories. However, national inventories with site-specific recovery projects might not cover the full recovery potential of SRM in a country. The United Nations Framework Classification for Resources (UNFC) is a tool for sustainable development of mineral resource endowments. In recent years, it has been further expanded from geogenic to anthropogenic resources. Yet, the current framework is mainly used to classify site-specific recovery projects based on viability for raw material production. The objective of the presented study is to use a national case study to understand the requirements for enabling the UNFC to classify anthropogenic resource projects and thus the future availability of SRMs on a national level. Furthermore we aim to provide guidance and feedback on reporting the results to resource policy makers, regulators and administration, investors and NGOS to allow objective and evidence-based decision-making toward a more circular economy.

To apply the UNFC, factors are used to evaluate the potential of resource recovery projects based on the three UNFC criteria “Environmental-Socio-Economic Viability”, “Technical Feasibility”, and “Degree of Confidence in the Estimate”. The final classification, which leads to the maturity level of the project, is a combination of these three criteria and is presented in a three-digit UNFC class. The shown Swiss national case study assesses the economic viability and environmental impacts of removing embedded electronic devices from end-of-life vehicles (ELVs) to recycle them separately in waste electrical and electronic equipment (WEEE) recycling facilities. The case study includes a dynamic material flow analysis (dMFA) coupled to a model for material recovery potential, a life cycle assessment (LCA) and an economic analysis. An adapted version of the UNFC is tested to this case study in a continuous process to make it applicable for national accounting. Making UNFC applicable on national level may require adaptions in methods, tools and needed data compared to site-specific assessments of the results. Moreover, it is crucial to standardize the factors, methods, and translation of results into the UNFC classification to achieve the necessary comparability. The Swiss case study aims to identify hurdles that could prevent the implementation of a recovery project and even goes a step further by designing factors and methods to overcome these hurdles.

Expanding the UNFC from a site-specific project level to regional and national level addresses the need for accurate, consistent, and comprehensive information and planning strategies for secondary raw materials. The results of this study will contribute to the development of a transparent and objective methodology for assessing the availability of SRMs on a national level.

Business agreements in industrial symbiosis relationships – a categorisation and suggestions for practice and research

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Murat Mirata [1], ***Katrin Katana*** [1], ***Mikael Ottosson*** [1]

***1.** Linköping University*

Industrial symbiosis (IS) represents long-term relationships among actors from diverse sectors creating additional economic and environmental value by more productive usage of residual resources and by joint utility-, and service-innovations. Although operational cases show their significant potential (e.g. Martin and Harris 2018, Fan et al. 2017), IS practices remain under-developed and associated environmental and business benefits remain unharvested (Boons et al, 2017). Business agreements that effectively reduce uncertainty, manage dependency, and incentivize collaboration are crucial in establishing all forms of inter-organisational relationships (Dyer and Singh, 1998). Business agreements are also key in the emergence and development of IS practices (Andrews, 2001; Albino et al.,), which are essentially inter-organisational relationships, whose key characteristics can differ significantly from conventional business transactions. Improved knowledge on relevant elements and characteristics of business agreements employed in different IS cases, and on their functions, can therefore play a vital role in catalysing new IS developments by assisting the formulation of more supportive business agreements. To this date, however, both research and knowledge on business agreements in IS relationships remain highly limited.

To close these gaps, our research drew upon inter-organisational relationship perspectives established in management literature and explored IS collaborations and business agreements in multiple qualitative case studies. While studying more than 20 operational and emerging cases, we focused on key characteristics of the IS relationships – such investment requirements of enabling assets, available alternatives, and return expectations–as well as the elements of employed business agreements – including ownership and responsibility structures, terms of non-compliance, compensation/pricing mechanisms and agreement durations.

As a result, our research delivers three main scientific and practice-oriented contributions.

- Firstly, we introduce a categorisation of IS relationships by grouping them as those involving low-, medium- and high-level of dependence and integration among partners.
- Secondly, based on our case findings, we provide numerous suggestions for contractual and relational arrangements to effectively manage key characteristics of IS relationships in different categories. These include, among others, suggestions on ownership, responsibilities and liabilities, management of supply and demand risks, as well as mitigation measures.
- Thirdly, we provide suggestions for future research directions regarding governance mechanisms and business agreements within the IS field.

Implementing circular management practices in Mediterranean forests: an environmental assessment of a biorefinery plant

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Forests cover 35% of Europe footprint area. In Catalonia (Spain), Mediterranean forest cover 43% of their territory, and the lack of management practices in a climate change scenario is rising forest fires due to the amount of accumulated biomass stock. Today, forests orography and high slopes are responsible of the low profitability of forest by-products. Within the BIOREFFORMED project (LIFE19 ENV/ES000544), we aim to boost the sustainable Mediterranean-forest management practices by adding value to the forest value chains. The objective is to contribute to the development of the bioeconomy helping to accelerate progress towards a circular and low-carbon economy. In this work we assessed the environmental performance of a pilot biorefinery plant (TRL7-8) located in Catalonia capable to transform waste biomass stock (using 45ha of forest demonstration stands) into several by-products such as aromas, antioxidants or sugars from pyrolysis oils and biochar to produce energy. This innovative approach combines an existing thermochemical plant with an extraction unit that can obtain value-added products. To ensure such circular strategy is aligned with an improved environmental performance, life cycle assessment was used. We tracked all energy and material inputs and outputs from a real-case biorefinery plant within the different final products obtained. Further, we allocated environmental burdens from all system processes into all co-products following ISO14044 for multifunctional systems. Preliminary results show the energy expenditure of electric resistors from the thermochemical plant are dominating environmental impacts, followed by the forest management practices due to transportation needs. To provide sustainability assessment, we compared the derived environmental impacts from the biorefinery co-products with those derived from current supply-chains that provide the same function. The assessment will be also useful to compare the pilot plant here assessed with the equivalent industrialized processes in order to understand the potential scalability of results globally. Moreover, based on these results, further recommendations to improve the environmental sustainability of biorefineries will be given. The expected results will also provide new insights to improve bioeconomy practices and to deal with the environmental assessment of circular systems.

Life cycle assessment of geopolymer concrete made with tailings from ilmenite mining

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Simon Brekke [1], ***Reyn O'Born*** [2]

1. Norconsult, 2. University of Agder

Global CO2 emissions from cement production represent a major challenge on the path towards a future of net zero emissions. Concrete represents 5-7% of the total global CO2 emissions while remaining a critical building material in every continet. It is imperative to find low-emissions solutions that can reduce the overall global impact of concrete by finding new mixtures and binders for cement production, which are the main contributing factor for emissions from concrete. Alternative concrete binders are being developed, and one such binder is called geopolymer cement. Geopolymer cement is made by mixing industrial wastes with an alkaline solution, such as sodium or potassium hydroxide. This cement from waste can completely replace ordinary portland cement in concrete. In Norway, the company Saferock is developing a new geopolymer cement which utilises mine tailings from ilmenite production combined together with potassium hydroxide. Today, millions of tons of mine tailings are deposited in a region called Sokndal, which is a major environmental concern, but offers more than 100 million tons of easily accessible materials for Saferock to use for producing geopolymer cement. It is important when working with alternative materials to understand their environmental impacts and to see if they are beneficial for exploitation or not. Thus the purpose of this study is to evaluate the environmental impacts of Saferock's geopolymer cement. This is done by using life cycle assessment (LCA) to quantify the emissions that come from producing the geopolymer cement and concrete.

The results of the LCA study show that the CO2 emissions from the geopolymer concrete are exactly half of those of a comparable standard concrete. The potassium hydroxide accounts for 90% of the emissions; however the background data on the emissions from this process are insufficient. It is recommended that Saferock acquire potassium hydroxide produced using renewable resources in order to further reduce their emissions. An LCA study was also carried out on a school building in the region of Ørsta to compare the impacts of different building materials in a wider system perspective. The school was modelled in standard concrete and compared to a geopolymer concrete variant. The results showed that the overall impacts from concrete were significantly reduced with the geopolymer concrete, but that further reductions could be made by modifying the school design further.

Design Solutions for Cost-Effective Passive Solar Housing in the United States

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jasmina Burek [1]
1. *University of Massachusetts Lowell*

A zero-energy building (ZEB) is an energy-efficient building which generates renewable energy on-site and offsets and/or exceeds the energy used from the electric grid. The most accessible and affordable on-site renewable energy source for residential buildings is solar photovoltaics (PVs). ZEBs must be 50% to 70% more efficient than conventional buildings. Thus, we choose a passive solar house design, which is a standard for energy efficient, comfortable, and affordable building with roof mounted solar PV system. A probabilistic building life cycle assessment tool for residential buildings called the Building Attribute to Impact Algorithm (BAIA) was used to analyze passive house embodied and operational energy and related environmental impacts and costs based on building geometry, assemblies, system attributes, regional U.S. electricity production, and climate zones. BAIA uses Monte Carlo analysis to simulate results for thousands of unique passive house designs. For the zero-energy requirement of the building, we created a solar PV model based on geometry outputs from BAIA to determine solar PV panel allowable size, energy production, total cost, and cost savings over their lifetime. We will present preliminary results for two cities, Boston in Massachusetts (MA), and San Francisco in California. The main differences between two locations were: energy cost, electric grid, and solar irradiation.

Teaching life cycle assessment with campus-based projects

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monica Rodriguez Morris [1], *Ian Aley* [1], *Andrea Hicks* [2]
1. University of Wisconsin-Madison, 2. Wisconsin

Campus-based projects engage and pair local interested parties with students who are taking classes in their campus. Two iterations of a life cycle assessment course for undergraduates were taught. In total forty students worked on three different campus-based group projects. Student's declared majors were diverse, some being environmental studies, engineering, and business.

A semester-long project was assigned as part of the course and students worked and collaborated on a project topic that was important to and requested by a campus entity. Project topics available to students were (1) comparing different sources of produce for campus dining, (2) packaging for "to-go" meals and items and (3) comparing different types of clothing reuse systems. Students worked in groups of three to four students for the duration of the semester. Some deliverables required as part of the project were a project scope, project inventory, impact results and interpretation due at different points of the semester.

At the end of the course, students submitted a written reflection where they reported on the aspects they found beneficial of the project structure and which aspects could be improved. In general, students provided positive feedback in that they enjoyed working on a project they felt had local impact and could truly impact decision-making. Students also reported positively in that they benefited from the biweekly shorter assignments that built towards their final project. On the negative aspects, students were frustrated with the more limited choice of projects as some would have preferred to suggest and select their own topics rather than have a pre-set selection of projects. Students also commented on the difficulty of putting into practice the functional unit. Additionally, students commented on how difficult it is to get started on an open-ended project. A recurring comment is that the students found it difficult to find data sources. Which is something that even seasoned experts confront frequently. However, in the second iteration of the course the project was planned with more time in advance with the interested entity, the scope was significantly narrowed, and some data was facilitated prior to the course start by the interested entity. The complaint of not finding data was less frequent in the student reflections in the second iteration of the course.

Campus-based projects can foster a sense of ownership and engagement to students that other types of projects may be lacking. To facilitate these types of projects, the scope needs to be somewhat predefined, especially for students who are new to LCA, and contact with campus entities needs to be established well in advance prior to the start of class to best source data and information for the students.

Introduction of OpenSankey, a free and open-source online software for interactive Sankey diagram visualization

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Julien Alapetite [1], Jean-Yves Courtonne [2], Fabrice Caini [3], Vincent Clavel [1], Alexandre Pannier [1], Emmanuel Krieger [2]

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Brief history. The OpenSankey project dates back to 2013 with an online Sankey software available on a website (eco-data.fr) along with its source code (https://github.com/eco-data/open-sankey). From 2013 to 2020, the software was incrementally improved and tested for the purpose of research projects (e.g., https://flux-biomasse.fr/resultats/sankey_bois/France). Real development efforts, however, only started in 2021 (i) to improve the user experience and (ii) to add new features.

Features. A few softwares are already available to draw Sankey diagrams: the most famous one is e-Sankey, but one can also mention SankeyMatic and Floweaver. The aim of OpenSankey is to achieve at least equivalent features than those available on e-Sankey on an easy-to-use free website. As of today, OpenSankey allows to:

- Automatically create a diagram from an excel file,
- Move nodes and links individually or by group,
- Change the appearance (form, color, logo) of nodes, links and associated labels,
- Add more info on links or nodes in tooltips,
- Tag links, nodes and data in order to filter them easily or two display them with specific color palettes (e.g., colors on the diagram can be associated to supply chains or alternatively to stages of production and transformation, or to years or regions),
- Manipulate hierarchies of nodes, i.e., aggregate or disaggregate them.
- Save the diagram in json, excel, or pdf format.
- Load new data using an existing layout.

Under the hood. OpenSankey uses javascript React framework which is great for modularity. It is also uses the D3 dataviz library. Operations linked to import/export of excel files are treated by python scripts.

Access. A pre-version of the software is already freely available online (open-sankey.fr) in English and French and is frequently updated. Version 1 will be released in May 2023 along with a few tutorials and examples. The source will be open around the same period and we hope a community of users will take it up. Note that TerriFlux develops and sells other softwares based on OpenSankey, which allow to handle more complex data set with multiple hierarchies and to to combine data reconciliation and other advanced dataviz features. However, the poster will focus on OpenSankey only.

Brine circularity in the desalination industry: case study of the Moroccan Atlantic coast

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hajar Abjeg [1], ***Paola Ibarra Gonzalez*** [2], ***Ana Somoza Tornos*** [1], ***Dimitrios Xevgenos*** [3]

1. TU Delft, 2. Technical University Delft, 3. Delft University of Technology

As global climate changes, the gap between freshwater demand and supply is continuously on the rise. Bridging the gap is critical for water-scarce North African countries like Morocco. Since the hydrosphere isn't reliable to meet the country's freshwater needs, the government is shifting its focus to generating freshwater via seawater desalination. The current projects in the regions of Agadir, Laâyoune and El Hoceima utilize the Sea Water Reverse Osmosis (SWRO) desalination method. This process pushes saline water through permeable membranes to separate freshwater from dissolved salts and minerals. Although desalination helps Morocco to fight water scarcity, SWRO has been shown to drive a high electrical demand, increase the concentration of certain minerals [PIG1] at the discharge point, as well as generate high volumes of liquid (brine) and membrane wastes[PIG2] . For the city of Agadir, brine waste could be particularly damaging to the local fishing industry. A promising solution for this issue could be re-using the SWRO brines. Therefore, the purpose of this project is to identify the most sustainable SWRO brine circularity applications for the region of Agadir. The first step consisted of performing a literature review to identify the various methods of re-purposing the SWRO brine, ranging from fertilization to mineral recovery. As a second step, the LCSP framework was utilized to select a list of sustainability indicators for evaluating the impacts of the re-use applications on the social, technical, economic, and environmental levels. A gate screening approach was then applied to select the two most fitting brine re-use methods for the region: algaculture and mineral recovery. Using the multi-criteria decision analysis framework, an evaluation was performed to evaluate both alternatives. Technical indicators were calculated using Aspen Plus, whereas social indicators were validated [PIG3] using stakeholder interviews. Economic indicators were quantified via benchmarking, and an LCA study was performed to understand the environmental implications of both applications. Finally, the best-worst method was applied to assign weights to the criteria, resulting in a systematic, holistic analysis of these two SWRO circularity applications for the region of Agadir on the Atlantic Coast of Morocco.

Closing the concrete loop – how to make it eco-friendly?

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Berfin Bayram [1], ***Kathrin Greiff*** [1]

1. *Institute of Anthropogenic Material Cycles (ANTS), RWTH Aachen University*

The circularity gap report in 2023 has shown that global economy is becoming less circular with each passing year. As a major construction material, non-metallic mineral extraction has experienced the sharpest growth, with an increase of almost fivefold in the last 50 years and currently accounting for 42.8 billion tons, nearly half of the world's total material production. The construction industry is not only the main source of resource consumption, but also waste generation, accounting for 35% of the total waste generated in the EU-27. Although the recycling rate of construction and demolition waste (CDW) is relatively high (88% in the EU-27), recycled aggregates (RAs) are mainly used in road construction, and the use of RA in structural concrete is currently limited. To achieve circular economy in the construction sector and reduce the use of primary material input as much as possible, the use of RA in structural concrete plays an essential role, as building construction market has been growing. With the aim of closing material loops, the use of RA in structural concrete has gained attention from both CDW recyclers and construction companies. However, similar to all other recycling systems, using RA in concrete is not always more eco-friendly than using natural aggregates (NAs), as there are various parameters to be considered in the environmental assessment. In order to show the environmental potential and limits of RA concrete, a comparative life cycle assessment (LCA) for concrete production with RA and NA is carried out within this study. Some key parameters: transportation distance, concrete mix, composition of CDW, and avoided impacts are further evaluated. Different scenarios on each mentioned parameter are conducted to highlight their influence on the results and identify the environmental potentials and limits of RA concrete. Transport distance (ratio between NA and RA distance), concrete mix (cement input and RA content) and avoided impacts are observed to be the main parameters with the greatest influence on the results. Further assessments are included to find out the scenario with the highest environmental benefits for recycled concrete. The use of RA in concrete production is an essential step in the circular economy; however, to achieve a sustainable circular system, the parameters evaluated in this study are important to make environmentally sound decisions. Future research could explore the economic aspect and its role in closing the concrete loop along with an eco-cost analysis.

Generating Resilience in the Entrepreneurial Ecosystem: A Community-Based Approach

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Haorui Wu [1]***, Kyle Breen*** [1]***, Meghann Coleman*** [2]***, Erin Wynn*** [2]***, Luke DeCoste*** [2]

1. *Dalhousie University,* ***2.*** *MindFrame Connect*

Climate change and climate-induced Consequently, disasters have been increasing in frequency, intensity, magnitude, and scope, threatening all communities on the earth. Industrial ecology fundamentally contributes to the resilient and sustainable development of our societies in the global context of climate change and disaster. Building the resilience capacity of entrepreneurial teams enables them to better cope with these disasters, further promoting their societal contribution. This is critical for Canada because Canada is warming at twice the rate of the global average and the Arctic is melting three times faster than the global average. This project applies a social ecology approach to contextualize the entrepreneurs' individual and collective resilience capacity in community settings by (1) building entrepreneurs' capacity to navigate the community-based resources (e.g., environmental, health, social, and cultural) to support, maintain, and enhance their and their teams' health and well-being, and (2) generating entrepreneurs' capacity to facilitate community-based resources to serve them and their teams in culturally meaningful ways. This project employs a qualitative approach, recruiting and conducting in-depth interviews with 60 entrepreneurs and their team members from the 13 provinces and territories across Canada to (1) systematically examine the community-based diverse resources supporting entrepreneurs and their teams' health and well-being; (2) to deeply identify the entrepreneurs' benefits and challenges of using these community-based resources; and (3) to provide evaluations and best practices in entrepreneurial resilience for those at the incubator/accelerator level to enhance the entrepreneurial ecosystem holistically. These outcomes support the entrepreneurs to better facilitate different community-based resources to serve them and their teams in diverse community contexts (e.g., disaster and emergency). The Canadian findings shed light on valuable references for international entrepreneurial teams to build their resilience capacity to arrange community-based resources to deal with climate change, disaster, and other crises.

Material Flow Analysis of the Tin Supply Chain

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jessie Bradley [1], ***Willem Auping*** [1], ***René Kleijn*** [2], ***Jan Kwakkel*** [1], ***Benjamin Sprecher*** [3]

1. *Delft University of Technology,* ***2.*** *Leiden University, CML,* ***3.*** *Technical University Delft*

Tin is an important metal for society that is vulnerable to disruptions. It is mainly used in solder that connects electronic components, which makes it essential for many new technologies, including electric vehicles and renewable energy technologies. Tin prices surged to an all-time high during the Covid-19 pandemic, and the anticipated increase in demand during the energy transition could put further pressure on the supply chain. A first step toward increasing the resilience of the tin supply chain is mapping it with Material Flow Analysis (MFA) to identify areas of vulnerability and improvement. Since previous tin MFA's, new developments have occurred that have not been analysed yet, especially when it comes to tin flows beyond unwrought tin and recycling of both pure and alloyed tin. We performed three types of global tin MFA: a geographical MFA for 2017, a sectoral MFA for 2017, and a cumulative sectoral MFA from 1927 to 2017. Each MFA gives insight into different aspects of the tin supply chain and allows the calculation of various indicators that can be used to determine circularity and criticality. Findings based on the geographical MFA indicate that tin supply is highly concentrated, reserve depletion time is lower than many other metals, and stockpiles have decreased significantly over the years, increasing the risk of supply disruption. Findings based on the sectoral MFAs indicate that a lot of tin has been lost, with almost three times as much tin in landfill and other waste stocks compared to reserves. A large amount of tin has also been lost in the steel recycling loop, where it is a contaminant that reduces steel toughness. Tin recycling is lower than previously assumed, with an End-of-Life Recycling Rate (EoL RR) of 16% and an End-of-Life Recycling Input Rate (EoL RIR) of 11%. In addition, average tin product lifetime is lower than most other non-ferrous metals. Substitution is also difficult, especially when it comes to solder, the largest and fastest growing application. Tin supply chain resilience can be improved by increasing exploration, diversifying supply, rebuilding stockpiles, and increasing circularity. Examples of specific areas for improvement include finding alternatives for solder, increasing the physical and emotional lifetime of electronic appliances, utilizing hibernating e-waste stocks, reducing non-functional tin can recycling, reducing manufacturing waste, and using new scrap recycling capacity for end-of-life scrap. In Europe, Tin may have received less attention than other metals because it was not labelled as a critical material by the European Commission. However, the new indicators calculated in this research would classify tin as critical, which could help stimulate efforts to increase the resilience of the European and global tin supply chains.

Bayesian networks for bottom-up component modeling in building stocks

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Nils Dittrich [1]***, Lombe Mutale*** [2]***, Ramon Hingorani*** [2]***, Jochen Köhler*** [2]***, Daniel B. Müller*** [1]

1. Norwegian University of Science and Technology, 2. NTNU

Building stocks are driving a large share of manmade GHG emissions and resource use through their construction, demolition, and use. Recycling materials and reusing components that already are part of the stock (often called urban mining) is a popular concept to reduce the environmental impacts of the building sector without degrowth. Facilitating the transition to these circular practices requires accurate and high-resolution information about the composition and dynamics of the building stock.

Material flow analyses (MFAs) of building stocks increasingly use bottom-up models and advanced machine learning to increase their resolution and accuracy. While these approaches seem to deliver improvements, they also introduce several challenges when compared to top-down models. They are highly data-intensive, but data with sufficient quality and coverage is scarce. Black box machine learning models often make the tools developed in a case study inapplicable to new system boundaries and also make it harder to interpret the results. Current studies often mitigate some of these problems by turning to predefined typologies for material intensity coefficients, which reduces the information about individual buildings and thereby the resolution of the study. Rules of design and correlations between different elements within buildings cannot be reflected in such an approach.

In this work we investigate the use of Bayesian networks, a white-box statistical model, to predict physical building attributes for use in MFA. The model draws on engineering design principles to manually create a causal network that connects different attributes of a building with each other. This makes it possible to connect widely available cadaster information and universal physical attributes like materiality and components. Rich data sources, which are available for few buildings, like building information models (BIMs), can be used to train the model for predicting the attributes of all other buildings, making this model highly versatile in its use. Correlations that are revealed in this process can easily be inspected visually, which makes it easy to validate them with expert understanding. Compared to black-box machine learning models this significantly increases the confidence in the accuracy of the predictions. While the resolution of Bayesian networks is in theory unlimited, the number of evidence points (buildings) for which we have complete knowledge limits the complexity of connections and number discrete states at each node, resulting in a limit for the achievable resolution.

Establishing this versatile bottom-up statistics approach contributes to recent advances toward more complex mathematical models in building stock research; at the same time, it invites more collaboration with disciplines such as civil engineering and architecture. The approach we demonstrate also has the potential to be used for a longer time by continuously expanding the Bayesian network as new attributes become of interest and more information becomes available.

Metrics for absolute environmentally sustainable foods – case on tunicate burger

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:35: Food Systems (short presentations) (B0.41 KOG)

Lars Gunnar Furelid Tellnes [1], ***Anna-Lena Kjøniksen*** [1]

1. *Østfold University College*

As food has a substantial contribution to several environmental areas, the food industry is developing new products with lower impacts. These products need labels and metrics so that the lower environmental impacts can be communicate with consumers. To make the right investments for such new products, it is important to know both current and potential future environmental metrics. For food products, it is highly important to reduce environmental impacts such as climate change, eutrophication, and biodiversity. These areas are all major importance according to the planetary boundaries concept. Within life cycle assessment (LCA) methods that are typically applied on products, there has been an increased focus on absolute environmental sustainability. For climate change and food, this has for instance been estimated to a limit of 0.5 kg CO2 per meal. The objective of the study is to assess methods based on LCA to evaluate the absolute environmental sustainability of new food products with a case study.

The case study focusses on products based on tunicate (Ciona Intestinalis), which is a marine invertebrate potential as feed ingredient and human consumption. It is newly registered as a feed material in the EU and salmon feed are among targeted applications. It also has potential for human consumption and a burger patty is being developed for the conscious consumer. Tunicates can be farmed similar to mussels, where they eat plant plankton. Nutritionally, tunicates are high in protein and omega-3 making it similar to fish meal. Environmentally it is interesting for its low land use, low carbon footprint and no feed production needed. The tunicate consumption of plant plankton is assessed to have a benefit to environment by nitrogen removal from marine waters.

The goal of the LCA within the study is to assess the potential impact of the tunicate burger patty and to compare with metrics for absolute environmental sustainability. LCA is applied and based on the framework for environmental footprint (EF). Special focus has been given to LCIA and eutrophication, as the impacts on nitrogen flows is of interests. To assess the absolute environmental performance, various criteria from literature is reviewed.

The results indicate that the climate performance of the tunicate burger is within the criteria for absolute sustainability. A large share of the impacts on climate change is linked to the diesel used in harvesting, while capital goods such as equipment and machinery also has a large share. For eutrophication, the results become negative in total as the effect of nitrogen removal are surpassing the other impacts. As there are no negative thresholds, weighting was applied to assess the total sustainability. With EF methods, the weighted results in total with all impact categories. The results indicate that the tunicate burger is well suited for absolute environmentally sustainable foods. Further work is however needed in making absolute criteria for covering all environmental impact categories.

Applying industrial ecology methods to fictional worlds: an example on the spice and water cycles on the planet Arrakis from Frank Herbert's Dune

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Romain Guillaume Billy [1]***, Daniel B. Müller*** [2]

1. Norwegian Univ. of Science and Technology, 2. Norwegian University of Science and Technology

Frank Herbert's Dune is one of the most famous works of science fiction, with 20 million copies sold and several movie adaptations. More importantly, it is considered one of the first science-fiction novels with a strong ecological focus. Herbert used the ecosystem of the Oregon coastal dunes as a source of inspiration to design the desertic planet Arrakis, arguably the main character of the story.

Despite sharing some characteristics with the Earth, Arrakis is much warmer. The planet mostly consists of mountainous areas and a large desert. Despite its extreme aridity, this desert hosts an original ecosystem. Sandtrouts are attracted to the few underground bodies of water available and surround them, making them unavailable to the rest of the ecosystem and keeping the desert arid for their sandworm phase. Indeed, sandtrouts evolve into giant sandworms, who cannot survive in the presence of water. The transformation from sandtrout to sandworm also releases a special substance, called spice, or *mélange.*

The spice is the single most important substance in Herbert's fictional world: in addition to its geriatric properties that prolong the lifetime of humans, it enables fast interstellar travel, which is key for the cohesion of the galactic empire. Indeed, the importance of the spice and its addictive properties have already been compared to the role of oil in our current society. However, on Arrakis, the most critical resource is not the spice, but water. The indigenous population, the Fremen, survives in the desert thanks to their extreme adaptation to this arid environment. They use special whole-body suits that allow them to recycle most of the water they consume in a closed loop. In the book, the Fremen pursue a terraforming project of Arrakis. While turning the desert into a giant oasis makes the living conditions more pleasant for humans, this also leads to the destruction of the original desert ecosystem and by extension stops the spice production, raising issues of competing interests for resource exploitation, climate change, and ecosystem preservation.

In our work, we take Herbert's world as a starting point to showcase the use of some industrial ecology methods. We demonstrate the instability of Arrakis' ecosystem by developing a material flow analysis model for the spice and water cycles and their interactions. We then discuss the importance of these substances at the planet and galaxy scales with a criticality assessment.

In the same way that ethical issues raised by the progress of artificial intelligence have been discussed by authors such as Isaac Asimov long before becoming reality, science fiction allows us to question the relationships between materials and society with a greater freedom. Besides, we argue that this type of metaphor can be a powerful tool to disseminate industrial ecology research to students and the general population, while the potential additional media attention for this type of popular science exercise can increase population awareness on pressing earthly issues.

LIFECYCLE ASSESSMENT AND DESIGN BY SEAMLESS ANALYSIS FROM MATERIAL TO SYSTEM; CASE STUDY OF MATERIAL SELECTION OF THERMAL ENERGY STORAGE SYSTEM

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Shoma Fujii [1]***, Yuichiro Kanematsu*** [1]***, Yasunori Kikuchi*** [1]

1. *The University of Tokyo*

Decarbonizing industrial heat is important for climate neutrality. A thermal energy storage and transport system using a zeolite water vapor adsorption/desorption cycle would allow industrial waste heat to be transferred across space and time to nearby heat demand. The main targets of heat demand in many existing adsorptive thermal energy storage systems for low-temperature waste heat recovery of around 200°C have been hot water supply or space heating.

The objective of this study is to design the system of thermal energy storage and transport system using a heat discharging device named “zeolite boiler” that could be used for industrial applications. The zeolite boiler employs a moving bed and indirect heat exchange system to enable continuous generation of pressurized steam. Zeolite is continuously provided from the top. Humid air humidified by bubbling in warm water or steam generated by existed boiler is injected from the top to generate adsorption heat in the zeolite. The generated adsorption heat evaporates the feed water in the heat exchanger.Seamless connection of material properties such as equilibrium, kinetics, specific heat capacity, thermal conductivity, degradation, and heat transfer properties of zeolite, equipment properties such as heat exchanger length, chamber diameter, and operating conditions, and system properties such as region of application is important to design this kind of systems.

As an example, the properties of several zeolites, including degradation, were obtained experimentally and then incorporated into the numerical analysis of the heat charging/discharging devices. The numerical analysis of the devices was performed and validated experimentally. Using the experimentally validated numerical analysis, a full-scale system was designed, and inventory data for LCA was generated. The impact of different material degradation characteristics on lifecycle environmental burdens was evaluated, and the effectiveness of seamless connection from material to system was confirmed.

Modeling the current and future flow of post-consumer textile waste in Flanders and the Netherlands

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Veerle Vermeyen [1], *Luc Alaerts* [1], *Karel Van Acker* [1]
1. KU Leuven

Today's textile consumption is highly linear, depending on virgin resource extraction and resulting in significant amounts of waste. To change this, the European Union aims to transform the value chain significantly in the coming decade, as outlined in the European Green Deal (2019) and EU strategy for Sustainable and Circular Textiles (2022). The EU directive on waste further requires the separate collection of textiles from households by member states as of 2025. Also, additional requirements on sorting before export are being considered because the export of low-quality used textiles carries the risk of an undesirable end-of-life treatment in receiving countries. All these initiatives are expected to significantly increase the amount of textiles being collected and sorted in Europe.

The enhanced selective collection of the post-consumer textile waste stream combined with the decreasing quality of new clothing is anticipated to significantly increase the amount of non-reusable materials available. For these textiles, closed-loop fiber-to-fiber recycling is one aspect needed to increase the circularity of the textile value chain. Increasing the use of closed-loop recycled fibers can aid in decreasing the virgin raw materials required and waste generated. For closed-loop recycling to succeed, a constant and uniform feedstock from the waste stream is essential. Especially the fiber composition is an important factor, with single fiber textiles being more straightforward to recycle than fiber blends. Further, different fiber types require different recycling processes. Hence for governments to set the appropriate policies and for companies to make suitable investments, a deeper understanding of the current and future quantities of post-consumer textiles, and the composition, is required.

My research aims to provide insight into this through 1) the creation of baseline MFAs for the current post-consumer textile stream in Flanders and the Netherlands, including the fiber composition of the non-reusable fraction, and 2) create future scenarios for both regions based on changes in the collection, sorting, and recycling rates. The baseline MFAs will be created based on secondary data collected from the available scientific and non-scientific literature, official reports, and public statistics. The resulting baseline MFAs will provide a regional overview of the current end-of-life flow, showing bottlenecks and revealing current differences in the efficiency or inefficiency of handling discarded consumer textiles between the regions. The scenarios will be built by adjusting the key parameters in the baseline MFAs, considering (upcoming) European and regional policies, and contemplating what is realistic based on the currently available best practices in other European member states. The data for the baseline MFA and the key assumptions in the scenarios will be validated through strategic stakeholder consultations. To summarize, this research aims to add much needed robust and representative regional data on the flow and composition of the consumer textile waste stream in Flanders and the Netherlands, and explores over space and time how to achieve better textile waste management.

Material Flows and Efficiency

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jonathan Cullen [1], ***Daniel Cooper*** [2]

1. University of Cambridge, 2. University of Michigan

Attempts to track material flows and the calculation of efficiency for material systems go hand in hand. Questions of where materials come from, where materials go to, and how much material is lost along the way are embedded in human societies. This talk presents a review of material flows, their analysis, and progress toward material efficiency. We focus first on material flow analysis (MFA) and the three key tenets of any MFA: presentation of **materials**, visualization of the **flow** structure, and insight derived from **analysis**. Reviewing recent literature, we explore how each of these concepts is described, organized, and presented in MFA studies. We then review the role of MFA in material efficiency calculations and what-if scenario analysis for informed decision-making. This includes an investigation into the origins and motivations behind the material efficiency paradigm and the key efficiency strategies and practices developed in recent years. We conclude by suggesting priorities for a future research agenda for material flows and efficiency.

Environmental assessment of source separated urine management. Comparison of three management scenarios in the ICTA-UAB building

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Virginia Maiza [1], Veronica Arcas Pilz [1], Anna Petit Boix [1], Joan Muñoz-Liesa [2], Xavier Gabarrell i Durany [1]

1. Universitat Autònoma de Barcelona, 2. Postdoctoral researcher UAB

Almost 75% of nitrogen fertilizer is synthesized from atmospheric N_2 through the Haber-Bosh process (Martin et al., 2023), which can account for 10 times more energy than K and P fertilizer production (Khan and Hanjra, 2009).
One waste fraction that is considered highly suitable for fertilizer production is source separated human urine. While only making up for 1% of the total wastewater fraction it contains up to 80% of nitrogen (Chatterjee et al., 2019).
The present work aims to understand the potential of urine in urban agriculture systems, focusing on the case of the ICTA-UAB building in the Universitat Autònoma de Barcelona. This building contains a rooftop greenhouse which houses hydroponic agriculture systems mainly fertilized through mineral and synthetic nutrients compounds.
On the other hand, the wastewater streams from the building toilets are connected to a biofilter in the front yard, where the separated diluted yellow water is discharged.
A connection between the current source separated urine form male urinals and the greenhouse irrigation system has been proposed within the BINAFET project, aiming to reduce the plant production footprint through building-greenhouse synergies.
To further understand the potential environmental benefits or constraints of this nutrient recovery a Life cycle analysis (LCA) is being performed of the current water treatment installation including the biofilter - which reduces the flow of wastewater going to a wastewater treatment plant (WWTP) - to further compare this scenario with two others:
· The recovery of nitrogen from source separated urine with its adequation in an aerobic reactor to be further repurposed as N fertilizer in the building integrated greenhouse.
· A conventional wastewater management discharged to a WWTP.
The methodology will focus on the definition of the three aforementioned scenarios to provide information for the performance of an LCA. To do this, the methodology will follow the ISO norms 14040 and 14044 with a definition of a goal & scope, system boundaries and the compilation of a life cycle inventory with the installation materials and processes relevant for the three scenarios. For the environmental footprint calculation, the Simapro 9.1 software will be used with the Ecoinvent 3.7 for the inventory selection. The impact categories will be chosen relevant to the scenarios with special focus on global warming, marine- freshwater eutrophication and fossil and mineral resource depletion.
A preliminary functional unit chosen is 1m3 of treated urine with the option to a second functional unit considering other stakeholder needs.
The inventory information will be based on the existing installation, the implementation of the aerobic reactor with the collaboration of the installing company and finally on literature data for the conventional wastewater treatment scenario.
With this work we aim to provide useful insights for urban and building stakeholders on how to better implement nutrient recovery strategies from an environmental perspective.

The expected results will define the basis for the BINAFET project to better understand the environmental footprint of the linear and circular flows proposed, focusing in this case on the nutrient recovery and use from the building wastewater.

Another outcome expected to be driven by this work is to further change the social perception on the use of wastewater streams for local production of goods.

A CONSTRUCTION PRODUCTS' CARBON FOOTPRINT DATABASE IN SUPPORTING ZERO CARBON INFRASTRUCTURE DESIGN: A METADATA ANALYSIS OF SIX CARBON FOOTPRINT DATABASES

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Shih-Hsien Yang [1], ***Hoai-Nam TRAN*** [2], ***Ching-Wei Yang*** [1], ***Bo-Kai Chiou*** [3]

1. *National Cheng Kung University,* ***2.*** *Duy Tan University,* ***3.*** *Industrial Technology Research Institute*

Transportation infrastructure contributes a significant portion of global greenhouse gas (GHG) emissions and has the potential for large-scale impact reductions. Reducing the whole-life impacts of the transportation system is critical for creating a net-zero carbon-built environment. In this regard, how to quantify the carbon footprint (CF) scientifically and accurately produced by construction activities to achieve zero carbon goals has been widely discussed by scholars. Accounting for the carbon footprint is critical for developing evidence-based action plans for climate change mitigation in transportation project developments. One crucial aspect of CF quantification is data acquisition for inventory data analysis. The majority of the existing CF studies adopted national-level databases, such as the national databases in the US, such as US Environmentally-Extended Input-Output (USEEIO) Models, and the Portland Cement Association database. Also, many existing studies used inventory databases in commercial software programs, such as Ecoinvent and Gabi 4. However, the CF evaluation for material consumption in transportation infrastructure projects presents limitations between the construction project location and where the CF database was made, lack of transparency, and/or the unsuitability of the data to the project conditions. Therefore, to develop CF data suitable to specific locations, it is necessary to establish a review of the existing database.

This study analyzed the six databases in Taiwan and other countries (i.e., (1) Ecoinvent in Switzerland, (2) GaBi in Germany, (3) CF database of Taiwan Environmental Protection Agency, (4) USEEIO in the United States, (5) LCBA Building Materials in Taiwan, and (6) ICM database in Australia in terms of five categories and 15 specific column designs of product information. They are (1) the system boundary (time, geography, and scope), (2) technology (process description, process map, and input-out), (3) data (product category, functional unit, Life cycle inventory (LCI) method, quantification, data quality), (4) document (latest updated date, creator information, and reviewer information), and (5) source of information (source of information). This meta-data analysis provides clear information for civil and environmental engineers to fulfill their different needs. This database also linked the CF data of various construction products to the construction specification codes specified by the public construction commission (PCC) in Taiwan. The linkage can greatly assist civil engineers to effectively and efficiently perform the CF quantification of their projects. Therefore, civil engineers can find adequate information and take quantitative actions in the planning and design stage to aim for a low-carbon strategy for infrastructure engineering.

Material cadastre and its application to forward circularity in the building stock

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Karin Gruhler [1], Georg Schiller [1]

1. Leibniz Institute of Ecological Urban and Regional Development

Resource consumption in the construction sector accounts for a large share of global material flows; 35-45% results from the provision of building materials. Savings must be made here. The material stock of the building stock must be understood as an anthropogenic resource, the use of which can contribute to saving natural resources through urban mining and recycling. To this end, it is important to know the building material stock and its dynamics, what quantities of material are contained in the buildings, what quantities of demolition are released through demolition and what quantities of building material are needed for new construction. Material cadastres (MC) help to provide corresponding knowledge and to model possible developments.

In this article we present the concept of the regional MCs. We show possibilities of simulating material cycles and associated resource consumption and emission loads. The basis is formed by typologies to describe the building stock and specific material composition indicators (MCI) to quantify the materiality of the stock. The MCIs are structured in such a way that, starting from the building material, the necessary raw materials on the input side and the emissions on the output side can be derived. For the extrapolation of the material stock and its flows, we use a bottom-up material flow approach. For quantification of the stock, we use geodata from the official real estate administrations.

Based on selected process chains, we show in simulations how recycling of municipal construction demolition waste affects resource consumption in new construction. The focus is on concrete demolition and its processing into recycled aggregate (RC-A) for concrete production. Based on assumptions on future construction activity, we simulate quantities of RG-A that result from demolition and that are needed for new construction. Municipal stakeholders are thus provided with important information. This helps to better assess supply and demand of RC-A at local level and to close regional cycles. This saves resources, contributes to secure raw materials and to the reduce GHG emissions.

Estimation of Recycling Potential of Construction Materials: Five Approaches

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Matan Mayer [1]

1. *IE University*

Recovery and reutilization of materials are regarded as key strategies for reducing greenhouse gas emissions in the built environment. Within those end-of-use scenarios, recycling is one of the widely used tactics, demonstrated by established infrastructure and developed supply chain networks in many geographic locations. While recycling is an increasingly common practice in the built environment, accurately defining recycling quality in order to compare technologies and material types remains methodologically contested. This is mainly due to the vast spectrum of scenarios that typically fall under the term 'recycling'. Remanufacturing, downcycling, upcycling and even direct reuse are all referred to as types of recycling in non-scientific cycles, depending on the sector they occur in. The main challenge in assessing the material recovery quality of those solutions is that they exist on a continuum without clear divisions. Take for example end-of-use broken glazing being processed into translucent glass sheets. Would that process constitute an improvement in material quality (broken glass being turned back into a continuous sheet) and therefore be regarded upcycling, or would it actually be considered a reduction in material quality (as the glass losses some of its transparency in the process)? This ambiguity directly impacts the industry's ability to determine recycling potential of construction materials.
Within that context, this presentation surveys and compares five recently published methods for assessing recyclability. The featured methods measure recycling potential from different perspectives: economic dimensions of the recycling industry; patterns of resource depletion; the energy cost of recycling; the carbon intensity of recovery processes; and the connection between recycling and human health. The scientific foundations of the five methods are presented and a range of widely used construction materials are tested. The performance of each material is then compared across the five assessment methods to note observations and gain insights. Some of the materials are found to consistently outperform others, whereas some materials perform well on one method while performing poorly on others. This comparative assessment is followed by a discussion that looks at the limitations of each approach and reasons, or lack thereof, for adoption of one method over the others in industry and academia. Additionally, the presentation discusses ways in which the methods could be combined in order to give a holistic view of recycling potential. Lastly, the presentation looks at future research trajectories and examines the path ahead for recycling in the construction industry.

Sustainable consumption – moving from niche to mainstream

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:35: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Göran Finnveden [1]***, Karin Bradley*** [1]***, Mikael Klintman*** [2]***, Jörgen Larsson*** [3]***, Matthias Lehner*** [2]***, Oksana Mont*** [2]***, Jonas Nässén*** [3]***, Åsa Svenfelt*** [4]

1. *KTH,* ***2.*** *Lund University,* ***3.*** *Chalmers University of Technology,* ***4.*** *Linköping University*

“Mistra Sustainable Consumption – from niche to mainstream” is a Swedish eight-year research program aiming to provide a knowledge base that stimulates a transition to more sustainable consumption. The goal is to contribute with knowledge on how sustainable consumption that is currently practised by a few can be scaled up and become more common. The program is interdisciplinary and transdisciplinary and collaborates with societal partners from businesses, governmental agencies, municipalities, regions and NGOs. There is a focus on food, holiday travels and homemaking, but other consumption areas are also considered. The research explores the roles, strategies and practices of policymakers, businesses, NGOs and individuals. The program is currently more than halfway, and this paper aims to present examples of key results so far and outline planned studies.

Our scenario studies conducted in the program in collaboration with others have shown that a combination of technological and behavioural changes is necessary to reduce consumption-based emissions of greenhouse gases (GHG) by 90 % until the year 2050. Only technological changes that improve efficiency or behavioural changes would not be enough. One study demonstrated that the total GHG emissions from private consumption could be reduced by almost 40 % through currently available alternatives in three areas (food, holiday travel and furniture). On the one hand, it is significant that already today, without large investments or developments, GHG emissions from households, can be nearly halved. On the other hand, these levels are still far from being sustainable. More fundamental changes are also needed, such as strategies for sufficiency. One study tested a voluntary reduction of working hours in Sweden with a corresponding salary decrease. This increased well-being among both higher and lower-income groups and could also lead to decreased environmental impacts. Among the drawbacks was increased economic insecurity for some participants. New business models could also support a transition to more sustainable consumption. Some companies are testing models based on leasing, renting etc that could be more sustainable. These models are becoming accepted primarily for social and functional values rather than environmental reasons. New policy instruments are needed for more sustainable consumption. In the research program, many promising policy instruments in food, aviation and consumer durables have been identified and analysed. Public acceptance of sustainable consumption policies has been identified as a critical factor. To improve public acceptance of policies, fairness, effectiveness and targeting companies have been identified as keys. Synergies between different sustainability goals are also important for policy acceptance. Our research shows that significant health benefits and GHG reductions can be achieved if half of the current consumption of red and processed meat is replaced with vegetables and legumes. When developing policies, rebound effects are important to consider. However, our latest publications demonstrate that more climate-friendly behaviour of environmentally committed consumers in one area (not flying, not owning a car, having a vegan diet or not living in a detached house) does not increase emissions in other areas. This finding goes against previous studies reported in the literature, and points to the need to further investigate how, and why, the rebound effect varies in different sectors and problem areas of consumption. See www.sustainableconsumption.se for publications from the program.

Evaluating circular processes with life cycle assessment: the case of denim jeans

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Erik Dekker* [1], *Lise de Boer* [1], *Anne van Bruggen* [1], *Frieke Heens* [1], *Vrishali Subramanian* [1], *Rosalie van Zelm* [2]**

1. National Institute for public health and the environment, RIVM, 2. Department of Environmental Science, Faculty of Science, Radboud University, Nijmegen 6525AJ

Considering current worldwide efforts to move from a linear to a circular economy, methods are needed to evaluate effective sustainable transition pathways. Not all circular processes are inherently safer and more sustainable than their linear alternatives, as, e.g., recycling processes also require material and energy inputs. Evaluating circular processes with life cycle assessment (LCA) is not always straightforward. Important questions arise about, among others, allocation of waste processes, gathering information on prospective processes, and importance of specific impacts. Toxicity is often disregarded in LCA's, while toxic chemicals can influence the safety of recycling processes or other circular strategies. Furthermore, consumption behavior, such as frequency of use and way of disposal, also influences circular strategies.

The goal of our work is to provide recommendations on how to address environmental evaluation of circular processes, including evaluation of toxicity. To compare linear versus circular processes, we performed an LCA case study on denim jeans. In this case study, we included the full life cycle from resource extraction up to waste treatment, comparing incineration, mechanical recycling and chemical recycling processes. To compile the inventory, we did a systematic literature search, and included information from different suppliers in the product chain. We paid additional attention to gathering data on chemicals, to be able to include toxic impacts in the assessment. We used ReCiPe2016 for the impact assessment, adding characterization factors for chemicals where needed. Also, we performed uncertainty analyses with Monte Carlo simulation on the various inventory parameters found in the literature.

Emergence of fast fashion and e-commerce pave the way to more rapid and effortless consumption, challenging the move toward a circular economy. The actual change therefore depends a lot on consumer behavior, such as how long they wear their clothes, and whether they bring their clothes to a second-hand store, to a collection point for recycling, or whether they throw it away with the household waste. Therefore, we included variation in consumer behavior and policy options as scenario analyses in our interpretation phase. Early results show the trade-offs in environmental impacts, such as global warming, water use and toxicity. In our presentation, recommendations will be provided to consumers and policymakers on how to steer the fashion industry towards safety, sustainability and circularity. The LCA provides a means to quantify the impact of circular policy options on safety and sustainability before implementation.

Cement life cycle analysis: what are the main factors influencing global warming?

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hiam Dahanni [1]***, Anne Ventura*** [2]***, Lauredan Le Guen*** [1]***, Michel Dauvergne*** [3]***, André Orcesi*** [4]***, Christian Cremona*** [5]

1. *University of Gustave Eiffel, GPEM-MAST, Campus of Nantes,* ***2.*** *University of Gustave Eiffel, MAST-GPEM, Campus of Nantes,* ***3.*** *University of Gustave Eiffel, AME-EASE, Campus of Nantes,* ***4.*** *Cerema, Research team ENDSUM, DTecITM/DTOA/GITEX, Champs-sur-Marne, France; Univ Eiffel, MAST- EMGCU, Marne-la-Vallée,,* ***5.*** *Bouygues Construction, Materials Engineering Dept., Paris*

The cement industry is at stake because it is globally responsible for 5 to 7% of total greenhouse gas emissions on Earth. This industry thus provides various strategies to reduce its contribution, mainly: reducing combustion energy by improving efficiency, reducing fossil fuels by replacing them by renewables or waste incineration, and substituting Portland cement by secondary resource obtained by recovery of industrial waste (called Supplementary Cementitious Materials, SCM). Reducing amounts of cement inside concrete by improving cement's properties is also another possibility. To evaluate if these strategies can decrease cement's environmental impacts, Life Cycle Assessment (LCA) is the dedicated method. The goal of this work is to determine, through a literature review, whether current cement LCA models can be used to simulate the cement industry's strategies described above. Thus, the first topic of this review investigates how the quality of cement is considered in the literature with respect to functional units and reference flows. We suggest a method for estimating the reference flow for the desired cement in accordance with the cement strength grade and fineness of cement. Then, our review looks into the potential key factors for the cement production process to decrease its contribution to global warming, investigating how different fuel options and the use of Supplementary Cementitious Materials are modeled in the literature. The study especially compares the amounts of energy used for heating, to the ones required for crushing and mixing ingredients (electricity), because this last energy is required to improve cement strength grade. The literature survey also investigates the significance of various allocation methods for SCMs with regard to environmental impacts.

The mineral basis of climate change mitigation technologies via the lens of patents

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Yang Li [1]

1. Harvard University

The world is speeding towards a cleaner energy and production system nowadays, which generates the fast-expanding demand of green products and technologies to reduce greenhouse gas emissions. It has been widely known that critical minerals play a key role in the implementation of green technologies, and there exist many works evaluating the characteristics of material flows of critical minerals.

However, the technology system is a complex system that co-evolves with the industry system all the time. It's necessary to combine the insights from technology evolution with the landscape of mineral flows. This study utilized over 5 million USPTO patents from 1976 to 2020 as a proxy of the technology system and examined the dependency of climate change mitigation technologies on 25 minerals (including Lithium, Cobalt, and rare earth elements) via the text mining of patent data and a combination of material flow metrics.

The analysis shows that: 1) 1/3 of all patents in the CPC climate change adaptation and mitigation technologies (CCMT for short) classification involve at least 1 of the 25 examined minerals after excluding the patents on mining and primary production of these minerals. As time evolves, CCMT on average involves more types of minerals within the same patent. 2) Each mineral has its specialized engagement in the technology domain. The analysis of revealed technology advantage index indicates: Lithium is mostly involved in the low carbon building, ICT, energy and transportation technologies, while Cobalt mostly in CCUS, industrial processes and transportation technologies. 3) Based on the co-utilization of minerals in patents, an evolving network (mineral space) was created to resemble the complementarity between mineral pairs, and another network of substitutability was created via the similarity of their physicochemical properties. It was found that the increase of material extraction of minerals significantly increased the utilization of complementary minerals, and the involved number of CCMT patents, and the utilization of substitutable minerals increase years after the shortage of supply and the invention of replacement technologies.

The study highlights the importance of interdisciplinary approaches in addressing the complex and interconnected challenges posed by climate change and the supply of critical minerals. A more predictive model of the interdependency of minerals and CCMTs and between different minerals will benefit our understanding of technology evolution and enable smart strategies to tackle related issues like development opportunities and supply risks.

Closing the municipal solid waste recycling gap in the United States

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Stijn van Ewijk [1], ***Koichi Kanaoka*** [2], ***Marian Chertow*** [2]

1. University College London, 2. Center for Industrial Ecology, Yale School of the Environment, Yale University

Waste recycling can reduce the environmental pressures of virgin material extraction, material processing, and waste disposal. The United States (US) currently recycles less than a third of municipal solid waste (MSW), which consists of packaging and other non-durable waste from residences and businesses. For some recyclable materials, including several plastics, the recycling rate is near zero.

However, the main reasons for this lack of recycling are unclear. Compared to other high-income countries, the US not only has a very low MSW recycling but also lacks the waste data that typically underpin decision-making elsewhere. Waste data collection in the US at the federal level is limited to a collation of industry data. Further data is collected at the state, local, and city levels, but these require further interpretation.

In this study, we present a detailed material flow analysis (MFA) of US waste generation, collection, treatment, and disposal for household and commercial waste. The data is collated from a large variety of sources, including the US EPA, state and local level reporting of recycling schemes, industry and consultancy reports regarding waste generation and the effectiveness of source separation, literature data on sorting efficiencies, and parameters estimated based on expert interviews.

The model, which is the first MFA that tracks the full path of MSW in the US, provides a detailed overview of the capture and loss of waste between the point of generation and its final destination (recovery or disposal). The preliminary results suggest that the low recycling rate of US MSW is mostly the result of two factors: many US citizens lack access to curbside recycling, and those who do have access, often incorrectly sort the recyclables.

The material balance underpins a dynamic model for assessing policy interventions to increase recycling, including the carbon implications. We found that a combined national roll-out of single-stream collection, additional post-consumer sorting, deposit-refund systems, and source separation of food waste could increase the recycling rate from 28% to 53% and save 171 Mt CO2e. We also found that no single intervention alone can substantially raise the recycling rate of the total waste stream.

Our results demonstrate the need for a national recycling strategy that combines a range of material- or product-specific interventions. At present, the US lacks such a national recycling policy and only features state-level and local initiatives. Finally, our analysis also shows the limitations of a focus on end-of-life waste management: an even further increase in recycling (beyond about 53%) would require profound changes much earlier in the product life cycle, including in product design, business models, and user behaviour.

Estimation of the material stocks of building in flood-hazard-area in Japan

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hiroaki Shirakawa [1], ***Yuya Ohta*** [1], ***Yuta Isazawa*** [1], ***Sota Nagata*** [1], ***Yuki Hiruta*** [1], ***Naho Yamashita*** [1], ***Hiroki Tanikawa*** [1]

1. Nagoya University

Every year there is a great loss of people's lives and poverty in Japan due to natural disasters. Floods are one of them. In particular, floods are feared to increase in the future due to the effects of climate change. Therefore, it is necessary to evaluate the amount of material stock in hazard areas in order to predict the amount of disaster waste generated and to formulate disaster prevention plans. On the other hand, it is very important to understand the trend of building construction in the hazard area, because a decrease in the number of buildings or material stock in the hazard area can reduce the damage.

Although several studies have been conducted to evaluate the amount of stock in hazard areas, most of them are limited to a relatively small area or a single year. On the other hand, since a large amount of disaster waste is generated in a short period of time, the estimation of disaster waste requires as high a spatial resolution as possible, and at the same time, as wide a range of estimation as possible is required for wide-area cooperation among local governments. Therefore, the objective of this study was to evaluate the number of buildings and the material stock of buildings in hazardous areas throughout Japan. The five years covered in this study were 2003, 2009, 2014, 2016, and 2020, for which building data were available.

Zmap Town II, produced by Zenrin Corporation, was used for the building data. Data on flood hazard areas are based on the "Flood Inundation Hazard Areas (2012 version)" provided by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT). Strictly speaking, the hazard area is considered to change depending on the state of infrastructure development, but for the sake of simplicity, it is assumed here that it does not change during the period under study. The data for the hazard areas are based on a 5-level (or in some cases 7-level) scale, where the areas that are expected to be inundated by flooding are rated according to the depth of inundation.

The analysis revealed the following points Buildings located in flood hazard areas accounted for about 25.4% of all buildings in Japan and did not change significantly over the study period. The composition of the number of buildings by flood depth level in 2020 was as follows: 37% were less than 50 cm, 21% were between 0.5 m and 1 m, 24% were between 1 m and 2 m, 16% were between 2 m and 5 m, and 1% were over 5 m. Tokyo has the largest number of buildings in areas expected to be inundated to a depth of 5 meters or more in 2020, followed by Chiba and Osaka prefectures.

We plan to further examine changes in the number of buildings and material stocks in more detail in the future.

Modelling the regional transformation to hydrogen-based green steel: An integrative and prospective material flow analysis of the North Rhine-Westphalian steel industry

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 10:15: Future resources (B0.31 KOG)

Rainer Radloff [1], ***Ali Abdelshafy*** [1], ***Grit Walther*** [1]

1. *Chair of Operations Management - RWTH Aachen University*

The production of primary steel is characterized by a high emission intensity. Due to its high coal consumption, the steel industry is responsible for around 30 % of industrial greenhouse gas emissions and thus for 5 % of total German emissions. In North Rhine-Westphalia, steel production accounts for up to 30 million tonnes or even more than 10 % of the state's total emissions. The enormous coal consumption is not only due to the high energy demand, but also to the process-related coal dependency of the classic blast furnace process.

For a far-reaching decarbonisation of the North Rhine-Westphalian industry, the introduction and rapid diffusion of new technologies and processes in steel production is essential. Two approaches are feasible: one is to maintain existing processes with retrofitted Carbon Capture and Usage or Storage, and the other is to avoid emissions through process changes (i.e. Carbon Direct Avoidance). Herein, direct reduction has emerged as a promising Carbon Direct Avoidance technique in the steel industry. All major German steel producers have announced specific steps to substitute coal-based feedstocks by switching to hydrogen-based direct reduction processes. If the hydrogen production and utilization of the steel producers are supplied by renewable energy sources, emissions can be largely avoided. However, this path is associated with far-reaching technical and procedural changes as well as a substantially increased demand for renewable electricity.

Hence, this study presents a case study from Western Germany via quantifying the changes in the regional material and energy flows in the state of North Rhine-Westphalia until the planned decarbonisation in 2045. The quantitative analysis firstly presents a detailed material and energy flow model that depicts the existing supply chain of the regional industry and intersectoral relations. Thereafter, a detailed process simulation model of hydrogen-based steel production is developed according to the industry's detailed technological plans to track the regional impacts of such a transformation to achieve zero-emission steel. In combination with different assumptions on the availability of green hydrogen and complementary climate reduction measures, the results of the process simulation are integrated into the material and energy flow model to map possible stepwise transformation paths until 2045. Here, the analyses show that with a maximum focus on hydrogen, more than 47 TWh of electricity from renewable energies could be required per year for these structural changes. Consequently, our work quantifies different approaches by which the decarbonization of the steel industry can be achieved with lower amounts of renewable electricity. For example, partial reliance on natural gas as a reducing agent in combination with the use of CCUS technologies can significantly reduce electricity demand for the transformation, especially in the medium term.

Expansion of Policy Domain of Sustainable Consumption and Production (SCP): Prospects for Envisioning-based Policy Making

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Yasuhiko Hotta [1]***, Tomohiro Tasaki*** [2]***, Ryu Koide*** [3]

1. Institute for Global Environmental Strategies, 2. National Institute for Environmental Studies, 3. Material Cycles Division, National Institute for Environmental Studies

The focus of SCP policy has shifted from management of environmental pollution to wider socio-technical change including infrastructure, lifestyles and business models that are sustainable over decades. The presentation first examines the expansion of the SCP policy domain through changes in focus of the following two aspects; product lifecycle policy and policy for changes in provision systems. The authors call for limiting lifecycle-based policy approaches to those that address a socio-technical transition to sustainability. They argue that transition-oriented SCP policy design proposed as envisioning-based policymaking (EnBPM) requires a new approach based on envisioning, social experimentation, a new indicator system to monitor the progress of transition, and development of a new business model. In doing so, they further develop the case for EnPBM and the present direction of potential policy research for developing EnBPM as a policy design approach.

CIRCULAR ECONOMY AND SUSTAINABILITY INDICATORS FOR THE VALORIZATION OF WINE PRODUCTION WASTE

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Wine sector represents a cultural, gastronomic and landscape heritage for Spain and Italy. Product quality, sustainability and environmental protection are playing an increasingly central role and can be observed on various levels of definition of programs and regulations. Some of the problems faced by this sector are the considerable amount of waste generated by agronomic practices and winemaking activities; the lack of valorization of some residues, for example, leaves and pruning wastes and, another problem is the limited number of indicators related to the circularity of wine production.

This contribution presents the design of a system of indicators for wine production and of a system of indicators to compare the valorisation of vine defoliation residues. The work was developed in Spain at the Universitat Politècnica de Catalunya - Barcelona Tech.

The work of valorisation of grape leaves, however, was carried out at the University of Campania "Luigi Vanvitelli" with the collaboration of the winery "Cantine Antonio Caggiano" of the Municipality of Taurasi, in Italy. to collect waste samples and receive support about the knowledge on viticulture and on oenological practices.

The reference system was defined through standard flow diagram relating to the production of red wine and through black box diagrams, specifying the inputs and outputs, for the two different valorisations of the same residue - Deep Eutectic Solvents based ultrasound assisted maceration (DES-UAM) and Supercritical Fluid Extraction (SFE).

The methodology is based on the design of a global system of industrial ecology and circular economy indicators related to wine production. Also, some indicators were chosen to compare the valorisations carried out with two different extraction methods using the same residue, i.e. the *Vitis vinifera* L residues.

The results show a comprehensive system of circular economy and sustainability indicators that has been designed and that is composed of 15 environmental indicators, 6 economic indicators and 7 social indicators. While for the comparison system relating to the two valorisation methods, 8 environmental indicators, 5 economic indicators and 7 social indicators were selected.

The comparison between the extraction methods used, DES-UAM and SFE, shows that both have the potential for advantageous effects both in economic terms by transforming grape leaf from waste into a profitable resource, and in social terms as it would enhance different expertise and foster research in this area. In terms of environmental impacts, SFE extraction appears preferable for the smaller quantities of inputs and outputs related to the process according to the black box diagram, however the DES-UAM technique makes use of a very simple process to perform, the molecule obtained is in its pure form and with a higher extraction yield, the use of traditional solvents is not eliminated but considerably reduced.

The valorization of wastes as products with high added value to support sustainable and circular production models is a way to integrate production culture into sustainable scenarios and explore the possible new fields of application.

The definition of indicators and measures of sustainability levels becomes a significant tool for analyzing the performance of an entire production context from the point of view of sustainability and to measure the degree of progress with respect to the circular economy and to sustainable development, to provide an overall picture and preliminary information of the environmental, economic, and social impacts of the valorization to be made.

Impact of energy transition and low-carbon technologies on reduction of embodied carbon in the built environment

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Alvin Wei liang Ee* [1], *Andre Yew* [2], *Minhee Son* [2], *Kendra Ho* [2]**

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The built environment accounts for 39% of the global energy related carbon emissions. 11% and 28% are from embodied and operational carbon respectively. Technological advancements in cooling, heating and energy efficiency will reduce operational carbon significantly. On the other hand, the embodied carbon of buildings, which come primarily from the materials and energy used in the construction of the buildings are more challenging.

Embodied carbon is the emissions associated with the supply chain of the materials, from its raw material extraction to refinement and transportation, and the construction of the building. Unlike operational carbon, which can be reduced over time, the embodied carbon of a building cannot be abated upon completion of the construction. Presently, embodied carbon can be managed through greening the supply chains of construction materials, green procurement and lean construction to reduce energy consumption during the construction phase.

With the impacts of climate change being more pervasive, there is increasing focus and pressure for countries to fulfill decarbonization targets. According to Climate Watch, as of 2021, 108 of 197 countries submitted new Nationally Determined Contributions with reduced total GHG emissions in 2030. Of these parties, 89 have communicated a net-zero intention. In many of these countries' Long-Term Emissions Strategies, addressing the energy mix of their country is an area of focus. This can be done through electrification, which reduces the need for carbon-intensive fossil fuels like coal and natural gas.

This impacts for the construction material industry, which is known to be energy intensive in its usage of cement and steel. Ongoing breakthrough studies to electrify the cement manufacturing process show that it is possible to produce cement with only electricity. Pre-commercial technology in the steel-making industry also looks at using electricity to directly refine primary steel instead of using traditional carbon-intensive coal furnaces. Electrification has also potential for processes such as the recycling of plastic pipes and steel.

However, electrification is not a one-size-fits-all solution. In cement production, the chemical reaction of limestone with clay in clinker production releases carbon dioxide. One strategy to help reduce emissions from such processes in cement production is carbon capture and storage. In the steel industry, an alternative way to decarbonize the industry without electrification is green steel, where the fossil fuels used in the production process are entirely replaced with hydrogen that is produced by electrolyzing water with renewable electricity.

This presentation will analyse the environmental impacts of a greener grid on the supply chain of key building materials and how alternative low-carbon solutions like green hydrogen and CCS influence their embodied carbon through the lens of Life Cycle Assessment.

The environmental sustainability of green roofs through Life Cycle Assessment: a review of layers materials and purposes

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Débora Fiorentin [1], ***Sandra Rafael*** [1], ***Mario Martín-Gamboa*** [2], ***Paula Quinteiro*** [1]

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Extreme weather effects related to climate change are a threat that cities are facing, meaning that urban areas are becoming more vulnerable to, for example, flooding and the urban heat island effect. Including green roofs (GRs) on new and also on existing buildings has been pointed out as an important strategy to overcome these issues. GR is a green infrastructure (GI), which is a vegetated roofing system that is functionally integrated into a roof area. GRs are aligned with SDG 11 by seeking greener sustainable and resilient cities and SDG 13 pursuing climate-resilient and climate-neutral cities.

GR are classified as extensive, semi-intensive, and intensive. Extensive GRs have low vegetation, such as sedum and grass, and the thickness of the growing medium is between 8 and 15 cm. The semi-intensive is an intermediary typology, allowing a variety of vegetation from sedum to small shrubs, with a 15 to 25 cm substrate layer. Intensive GRs can support a wider variety of vegetation, including lawn, shrubs, and trees, due to the minimum growing medium depth of 25 cm.

Several works have been performed to study the environmental impacts of GRs, through the Life Cycle Assessment (LCA) methodology, however, is still unknown what is the most environmentally sustainable GR. The aim of this work is to analyze methodological choices, i.e. functional unit, system boundaries, impact assessment methods, identify trends, and understand the effects of these choices on the environmental performance of GRs, in particular on global warming.

For this purpose, articles published in peer-reviewed journals focusing on LCA GR were considered. The final sample encompasses 40 case studies and 15 reviews. Within case studies, different scenarios involved in each case study were identified as 84 occurrences, corresponding to extensive (51), semi-intensive (11), and intensive (22) GRs.

This work shows that the methodological choices differed among the 40 case studies. Four system boundaries approaches were observed: 19 cradle-to-grave, 10 cradle-to-user, 5 cradle-to-gate and 6 cradle-to-manufactures. Different impact assessment categories were identified in the case studies, being global warming (kg CO_{2eq}) the most quantified impact category. The materials of the layers (e.g. insulation, waterproofing, substrate, root barrier) and the number of layers, ranging between 3 and 11, varied among the case studies. It is highlighted that materials manufacturing is the main contributor to the global warming impacts results, and within the types of layers, the main hotspot is the insulation. In this sense, this work contributes to the identification of the more sustainable GR, from the environmental point of view, identifying the materials and layers that have the lowest environmental impacts in the entire GR life cycle while still ensuring a GR's integrity and the building's proper operation.

Further research is needed for a comprehensive sustainability assessment of the GR, meaning that environmental, economic and social indicators should be considered. Additional investigation is required to evaluate the environmental impact assessment considering GR benefits, such as the improvement of building thermal performance.

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Monitoring needs for a resource efficient construction aggregates cycle in Norway

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jonna Ljunge [1], *Mark U. Simoni* [2], *Daniel B. Müller* [1]

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Construction aggregates (sand, gravel, and crushed rock) quite literally provide the foundation of modern urbanized society in the form of unbound groundwork materials and as principal components of asphalt and concrete. Driven by essential human needs for residence and transportation, aggregates now constitute the global majority of extracted solid materials by mass (OECD, 2019). In Norway, 60–70 Mt of aggregates enter the domestic market each year (corresponding to approximately 12 t per capita) while an additional 25–30 Mt are exported to the rest of the world (DMF, 2020, 2021, 2022a).

Challenges pertaining to resource efficiency and sustainability within the Norwegian construction aggregates cycle have recently received an increasing amount of attention. Analyses of currently permitted crushed rock reserves predict depletion within 10–20 years of local supplies to both Bergen and Trondheim municipalities (containing the second and fourth largest urban areas, respectively) (DMF, 2022b). The capital, Oslo, is already dependent on other municipalities to cover its demand for construction sand (DMF, 2022b), implying longer transports and increasing emissions compared to the national average (DMF, 2022c).

In addition, construction activity is typically associated with on-site removal of substantial quantities of geological material, particularly in the case of large-scale infrastructure expansion. Such pre-construction earthworks are not subject to the same licensing and reporting requirements that otherwise apply to mineral extraction in Norway (DMF, 2021; Miljødirektoratet, 2022) and are thus poorly documented and understood. Cautious approximations suggest that surplus masses generated, e.g., from excavation, blasting, and tunnel boring could produce material flows corresponding to ¾ of the total input of aggregates to Norwegian road construction (DMF, 2021). Instead of replacing primary production in traditional mines and quarries, these masses tend to be disposed of in structurally irrelevant landscaping structures, or even landfilled (Miljødirektoratet, 2021).

A system in which non-renewable resources are extracted from the lithosphere and transported for use at construction sites where equivalent materials are simultaneously removed holds an obvious optimization potential. However, the metabolic systems of sand, gravel, and crushed rock need to become much better documented in time, space, and quality to ensure robust prioritization of interventions aimed at improving resource efficiency. Here, we propose a systematic overview of the Norwegian construction aggregates cycle to highlight important monitoring gaps associated with key sustainability challenges.

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Estimation of alloying elements input through aluminum scrap to aluminum alloy production by alloy type

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Kentaro Takeyama [1], ***Ichiro Daigo*** [1], ***Takeo Hoshino*** [1]

1. *The University of Tokyo*

Aluminum is the second largest produced metal, and its demand has increased in recent years due to its useful properties. Environmental impact and primary resource consumption associated with aluminum production can be reduced by recycling. Current recycling process is regarded as cascade recycling. This cascade recycling causes physical and quality loss of alloying elements. Reduction of these loss leads to reduce resource consumption of alloying elements. Previous studies estimated the amount of aluminum scrap generation and alloying elements associated with aluminum scrap. However, they did not distinguish the input of aluminum scrap to secondary production process. In this study, we estimated the input of alloying elements input through aluminum scrap to aluminum alloy production by alloy type. To identify the supply-demand matrix of aluminum alloy to end-use products and that of aluminum scrap to secondary alloy production processes, we used RAS method-based technique with consideration for confirmed flow information. Dynamic material flow analysis was conducted to estimate the amount of collected aluminum scrap from each end-use product by alloy type. Alloying element contents in each alloy type was obtained from industrial standards. This method makes it possible to consider alloy to alloy recycling through products and scrap. From these results, input of alloying elements through aluminum scrap to aluminum alloy production by alloy type ware identified. In 2020 in Japan, about third of collected wrought alloy scrap was recycled into cast alloy production. Focusing on magnesium, about 60% of magnesium contained in wrought alloy scrap was consumed in cast alloy production. This equals to 25% of magnesium annual consumption in wrought alloy production. Wrought alloy from beverage can and automobile had the largest portion in magnesium input to cast alloy production. Magnesium input through wrought alloy scrap to cast alloy was larger than magnesium demand for cast alloy production, therefore, sorting technology for wrought alloy separation can be reduce physical loss caused by magnesium removal process in cast alloy production.

Optimizing Building Material Identification through Integration of Remote Sensing and Machine Learning Techniques

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Kun Sun [1], ***Gang Liu*** [1]

1. *University of Southern Denmark*

As cities and urban populations grow, the importance of reducing carbon emissions and improving energy efficiency in buildings grows. Building material identification is critical to achieving these goals because different materials have various energy efficiency properties and contribute differently to building's carbon footprint. The goal of this study is to investigate the potential of remote sensing and Google Street View in recognizing building roof and wall materials. We hope to accurately identify the materials used in the construction of roofs and walls by combining satellite imagery and high-resolution street-level photos, providing valuable information for energy efficiency assessments and urban carbon emissions accounting. The study's findings will have far-reaching implications for building energy efficiency and sustainability, as well as for renovation and retrofitting of existing structures. This research can also help to develop advanced technologies for building material recognition and provide strong technical support for quality control and project management.

Evaluation methodology of recycled content for metals

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 17:30: LCA and circularity (B0.25 KOG)

Taichi Suzuki [1], ***Ichiro Daigo*** [2]

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Recycled content (RC) is one of the well-known indices of recycling, representing the ratio of recycled metals used for a new product. It is used for an environmental claim of a product to highlight recycling awareness. The evaluation method of RC for a product is defined in ISO 14021 as “the proportion, by mass, of recycled material in a product or packaging,” and many products follow this definition. Based on ISO 14021, the RC of a product composed of metals can be calculated as the weighted average of the content of recycled metals used in the target product. It would be easy to calculate the RC if the metals were explicitly regarded as recycled or non-recycled metals. Therefore, to determine the RC of a product, the RC of a specific metal composing a product must be evaluated. The RC of metals is defined in the report by UNEP as “the fraction of secondary (scrap) metal in the total metal input of metal production.” The UNEP definition can be smoothly applied for evaluating the average of the RC of metals among all the applications in the system. However, the definition cannot be smoothly applied to the RC of a specific metal. When fabricating a specific metal, there is an input of scrap directly returned from a manufacturer to a fabricator, in addition to scrap purchased from the market. The UNEP definition cannot sufficiently differentiate such return and the scrap from the market. It may result in unfair evaluations, even overestimation, if such return is regarded as secondary raw material (SRM). To apply this definition for a specific metal, one should supplementally define the target process of the evaluation and inputs to the process.

RC of a specific metal shall represent the ratio of substance derived from secondary resources contained. Empirically, RC of a specific metal shall be quantified by using the information on the inputs to the fabrication process in which the chemical composition is determined. It is because the ratio of input of raw materials determines both chemical composition and RC. Once the chemical composition is determined, basically, it will not change in the following fabrication processes. We proposed the additional definition of SRMs as “input materials which are recovered by the waste management, and otherwise, they would have been disposed of.” Empirically, we defined a practice to refer to the origin of new scrap so that it can be clarified how much SRM is contained in the new scrap. Based on the definitions and practice above, we developed the calculation formula for RC for a specific metal. It follows two levels required for a specific metal; representative RC in a company or a factory level and individual RC in a specific batch level.

By applying our supplemental definitions and practice, the RC of a specific metal can be evaluated. An overestimation of RC can be avoided by referring to the origin of new scrap, though the conventional definition cannot. The proposed practice can evaluate comparable RC regardless of the system boundary set for the evaluation. To improve the RC, a fabricator is required to utilize traceable new scrap, as the new scrap without details of origin cannot be regarded as SRM. Thus, fair, comparable, and traceable RC for a specific metal can be obtained.

Impact Projection of Climate Change Adaptation Measures for Sustainable Urban Built Environment

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hiroki Tanikawa [1]***, Hiroaki Shirakawa*** [1]***, Yuki Hiruta*** [1]***, Naho Yamashita*** [1]***, Ichiro Daigo*** [2]***, Ippei Maruyama*** [2]***, Nagahisa Hirayama*** [1]***, Satoru Iizuka*** [1]

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This study will provide supportive information for discussing adaptation plans and measures for buildings and infrastructure facilities based on climate change scenarios. First, we will analyze and model the stock and flow of buildings and infrastructure facilities (roads, water, sewage) for Japan and then examine the impacts of different climate change adaptation scenarios based on spatial information. In order to examine this at the city level, urban structure level, and construction material level, the impact of adaptation scenarios for buildings and infrastructure facilities will be conducted by implementing the targets. From a multifaceted perspective of urban material cycling, energy, construction materials, urban meteorological phenomena, and urban economy, we will consider and further discuss strengthening urban functions and the possible impact on carbon emissions, lifetime change, and its impact on opportunities for new technology introduction, and increasing building and infrastructure stock that is vulnerable to climate change.

Estimation of hydrogen generation from Silicon sludge based on the Si-water-alkali reaction

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Taisei Kagawa [1], *Shunsuke Kashiwakura* [1], *Shoki Kosai* [2], *Eiji Yamasue* [1]
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Energy consumption has been growing in recent decades. The dominant energy sources are represented by fossil fuels such as oil and natural gas. The excess use of fossil fuels causes issues which have several aspects (e.g., environmental risks, energy security, and geopolitical). Therefore, the responsible energy source must be considered for the sustainable future. As the alternative energy sources, hydrogen can be a part of them. Because of the quantity is abundant in the earth, hydrogen is a reliable resource. Basically, it is eco-friendly resource when it is used for extracting energy by fuel cells or hydrogen internal combustion engines. However, it sometimes consumes fossil fuels to produce hydrogen. Therefore, we conducted a research of hydrogen production with no need of fossil fuels. Alternating the use of fossil fuels, we considered to use silicon waste which is generated in the semi-conductor industry. Due to the growth of the semiconductor and photovoltaic industry, the demand for Silicon is expected to increase, generating a massive amount of silicon waste. Despite it has high exergy

In recent years, the production volume of semiconductors has been increasing year by year due to the expansion of the high-speed communication standard "5G" and the expansion of demand for data servers, and it can be inferred that the production volume will continue to increase in the future. In the manufacturing process, only about 45-55% of single crystal silicon wafers are obtained, and the remaining is silicon sludge, which will be generated in Japan as of 2021 to about 8600 tons. At this stage, silicon sludge is only slightly cemented as an effective use, but most of it is landfilled or incinerated. Therefore, we decided to utilize silicon sludge, which is dominated by Si, for hydrogen generation.

($Si + 2H_2O \rightarrow 2H_2 + SiO_2$)

From the existing research, the reaction in which hydrogen is generated from silicon and water is used, but the reaction rate is extremely low. In this study, we tried to improve the reaction rate by adding alkali in this reaction.

The results showed that increasing the molar concentration of the alkaline additive, reducing the particle size of the silicon sludge, and increasing the temperature of the experimental environment were effective in improving the reaction rate. It was also found that alkaline OH- was consumed before and after the reaction.

($Si + 2OH^- + H_2O \rightarrow SiO_3^{2-} + 2H_2$)

and

($SiO_2 + OH^- \rightarrow SiO_3^{2-} + H_2O$)

There is a possibility that KOH can be obtained by electrodialysis membrane from the waste in the cement industry. Also Si sludge is gathered in the cement industry. Therefore, the research was finally conducted with the aim of constructing a waste-based hydrogen production system in cement industry.

Characterization of national Eco-Industrial Park projects in China, Korea, and Japan: Bibliometric analysis and systematic literature review

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Eco-industrial parks (EIPs) strive to promote sustainable industrial development by integrating environmental, economic, and social objectives. Despite the limited success of many national EIP programs, China, Japan and Korea have reported significant achievements in this field. This paper aims to characterize the three countries' national EIP projects to draw specific focus and implementation strategies. This study consists of two interrelated parts: 1) bibliometric analysis; and 2) the characterization of EIP development through a literature content analysis. The combination of ScienceDirect (Scopus), Web of Science (WoS), and Dimensions publication databases from 1998 until 2022 were used in this study. The bibliometric analysis was done by refining only the most-related literature based on the typical keywords and content, then visualized by using the VosViewer software for the keyword co-occurrence analysis. It was performed to analyze the EIPs research trend from 1998 to 2022. Based on the keyword co-occurrence analysis, the most popular keywords for EIP research in China are "industrial symbiosis" and "network". Meanwhile, "waste" is the most popular keyword in Japan Eco-town's publication; and "eco-industrial park" and "industrial symbiosis" are the most popular keywords for Korean EIP scientific publications. Based on further analysis, the focus of EIPs in China is resource efficiency and industrial upgrading through industrial symbiosis and networking. Korean model EIPs have a strong focus on innovation and technology in EIP transition, with a particular emphasis on industrial symbiosis development by business model based on triple bottom-line benefits. EIPs in Japan, or Eco-town projects, are characterized by a focus on waste recycling and the reuse of resources, as well as the development of sustainable infrastructure. Overall, the characterization of EIPs in China, Korea, and Japan is similar in selection and approval of EIP and business approaches, but they may differ in terms of their specific focus, priorities, and funding mechanisms.

How much material can be recovered by improving curbside systems? Insights from a US municipality-level collection model

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Karan Bhuwalka [1], ***Basuhi Ravi*** [1], ***Richard Roth*** [1], ***Elsa Olivetti*** [1]

1. Massachusetts Institute of Technology

Increasing material collection remains a fundamental bottleneck to improving dismal recycling rates in the US, and worldwide. Municipalities often differ in collection policies and we need to better understand how changing policies may impact collection rates. In this paper, we present a model that uses regression analyses to combine census data with policy parameters and estimate waste collection in every municipality in the US. The model estimates how changing policies such as increasing collection frequency or providing automatic participation in curbside recycling can increase recyclables collection across the country. We combine the collection model with a techno-economic model of material sorting, transportation and transportation to evaluate system costs. We use the model to quantify the subsidy needed to keep the recycling system viable and demonstrate the impact of expanded deposit return systems on the economics of curbside collection and sorting facilities. We find that there is potential to double the collection of residential recyclables in the US through supportive local policies.

Theory of Common Conflicts: Conceptualizing emergent ethics based view of social-ecological systems

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:14: Mitigation Policies (short presentations) (A1.44 KOG)

Saurabh Vij [1], ***Shauhrat Chopra*** [1]

1. *City University of Hong Kong*

Convergence of social, economic and environmental issues can be noted across the world. This can be evidenced through acceptability and popularity of goals, such as SDGs across institutes (e.g. in education, markets) and regions at different scales (e.g. cities, states, countries). This scenario, in our view, carries the potential, as evidenced by literature review, of developing into a normative position(i.e. a philosophical outlook of emergent ethics). It enables individual and collective responsible behaviour to ensure social, economic and environmental emergence at system level irrespective of local beliefs, values and religion. Such emergence for pre-defined time periods can be expected at different spatial scales (i.e. local, regional, national, global) for all locations. With such a top-down view, which is rarely considered in the study of socio-ecological systems (SES), how interactions might shape between users and how they can lead to social and ecological outcomes is the focus of our study. We are utilizing Elnor Ostrom's SES framework to conceptualize the proposed scenario, where all agents intend to reduce negative impacts for n-topics. Under this set-up, by utilizing axiomatic methodology, we identify all possible types of conflicts that can exist. The identification of conflicts is informed by the work of K Törnblom in conflict conceptualization. It is found that for the proposed SES conceptual frame (with key variables identified), if the normative position of ensuring social and ecological emergence for n-topics is embraced by all members of society, only a limited number of conflicts can exist. Since, the conflicts are limited only therefore the need of congruence between involved parties becomes also limited and as a result pragmatic possibilities of social-ecological systems modelling from a top-down view are opened up to identify set of possible future pathways for humanity.This fundamentally changes the view about the impossibility (as claimed by many including E. Ostrom) of not being able to realize empirical generalizations of the type of rules required for self-governing regimes located under nested settings. The only assumption made here is an all-inclusive embrace of emergent ethics, a philosophical outlook that does consider local normative priorities to ensure justice is delivered but only along with the contingency of ensuring emergence at system level that is defined with specific spatial and temporal bounds.The application of resulting theory informing about conflicts is demonstrated by showing its application to analyse the global issue of GHG emissions by various countries.

A parametric life cycle assessment model for ductile cast iron components

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Yongxian Zhu** [1], **Gregory Keoleian** [1], **Daniel Cooper** [1]*

***1.** University of Michigan*

Life cycle assessment (LCA) is widely used to evaluate product environmental impacts, while detailed LCAs are missing that model the effect of design and manufacturing decisions on U.S. ductile iron casting environmental impacts. We develop a parametric LCA model by collecting inventory data from 11 foundries (26% of U.S. production) and literature to quantify the impact of design and manufacturing decisions on the product's cu[1]mulative energy demand (CED) and global warming potential (GWP). The model reveals the cradle-to-gate CED and GWP of U.S. ductile iron products at 24–50 MJ/kgproduct (mean: 37 MJ/kgproduct) and 1.6–3.0 kg.CO2eq./ kgproduct (mean: 2.2 kg.CO2eq./kgproduct). A Sobol-indices sensitivity analysis revealed the factors that have the greatest effect in reducing these environmental impacts: casting yield, electricity grid, recycled content, and furnace technology. A comparative whole life cycle analysis of automotive ductile iron applications versus forged steel, stamped steel and aluminum alternatives highlights the design and manufacturing conditions that minimize life cycle impacts.

A Study on the Life Cycle Assessment(LCA) Methodology of In-situ Carbonation Technology Using CO2 emissions from Cement Industry

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Eunjin MOON [1], ***Joohyung Kim*** [1], ***Kyungmin Kim*** [1]

1. *Korea Conformity Laboratories*

In-situ carbonation technology is a mineral carbonation technology in the cement industry by injecting CO2 during the manufacturing process of cement-based construction materials. This technology can also reduce the amount of cement per unit. In this study, a basic design for LCA was conducted in order to analyze the technology optimization and compare the carbon emissions of existing process and developed process. This includes the system boundaries and unit process decision of the In-situ carbonation technology.

Preliminary work towards a cross lifecycle design tool for increased high-quality metal recycling

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Alissa Tsai [1], ***Yongxian Zhu*** [1], ***Seyed Heidari*** [1], ***Daniel Cooper*** [1]

1. *University of Michigan*

The embodied energy of U.S. vehicle structures is growing as energy-intensive materials such as aluminum auto body sheet (ABS) and advanced high strength steels (AHSS) are used to deliver improved performance. This presents an opportunity for recyclers to shift towards high-value recycling into wrought alloys and for car makers to increase the end-of-life (EOL) recycled content of their sheet, reducing their material costs and energy burden. However, the current system cannot effectively recycle the aluminum and steel sheets. Shredded and contaminated EOL metal (e.g., mixed aluminum alloys with steel rivets and mixed steel alloys with embedded copper wiring) is often exported, downcycled to castings, or recycled as rebar. In this poster, we will discuss preliminary work on developing a design tool that couples the effects of vehicle design, recycling system practices and technologies, and alloy compositional tolerances, under different ecosystem scenarios from 2020-2050 (e.g., continued dominance of internal combustion engine vehicles vs. rapid deployment of electric vehicles). Design and future R&D recommendations will be made using the tool to test the effect of cross-lifecycle design changes on the *system metrics*, which include cumulative energy demand (primary energy), greenhouse gas emissions, and primary metal demand.

Tracking the post-1990 sociometabolic transitions in Eastern Europe with dynamic economy-wide material flow analysis

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Wensong Zhu** [1], **Ciprian Cimpan** [1], **Kun Sun** [1], **Qiance Liu** [1], **Agate Veipa** [1], **Gang Liu** [1]*

***1.** University of Southern Denmark*

Developing and transitioning countries merit more attentions on resource monitoring and circular economy implementations to improve global sustainability. We tracked material stocks and flows within the socioeconomic systems of Bulgaria, Croatia, Poland, and Romania, four case countries in Eastern Europe which has undergone complex political and societal transitions during 1990-2019, by integrating economy-wide and dynamic material flow analysis principles. We show the countries, except Bulgaria, started to transfer primary manufacturing abroad when their per capita GDP reached 6800～7500 $/cap. Their per capita stocks reached 390 t/cap (Bulgaria), 383 t/cap (Croatia), 239 t/cap (Poland), and 306 t/cap (Romania) in 2019. Yet no solid evidence stood by saturated stocks or absolute decoupling along life cycles, but raw materials tended to decouple earlier from GDP growth than the flows closer to final consumption. Building and construction was the key sector for material accumulation and waste generation, thus crucial for promoting material efficiency and reduce material demands. A well-designed waste management systems and facilities as well as legislations need to be prioritized to maximize recycling capacities, particularly, for Bulgaria and Romania. Such sociometabolic patterns could facilitate discussion on resource productivity and decoupling, climate change mitigation, and circularity performance of the entire socioeconomic system.

Criticality assessment for a sustainable future

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ester van der Voet [1], ***Katharina Berger*** [2], ***Theresa Boiger*** [2], ***Annechien Hoeben*** [2], ***Moritz Kettele*** [2], ***Paul Krassnitzer*** [2], ***Antonia Pohlmann*** [2], ***Martin Popowicz*** [2], ***Katharina Roche*** [2], ***Julius Ott*** [2], ***Ruben Huele*** [3]

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The EU carries out criticality assessments to identify potential supply problems related to specific raw materials. The EU method is a risk approach, confronting the chances of a bad thing happening (supply risk) with the damage done if it actually does happen (vulnerability to supply risk, also called economic importance). This method, although it is useful as a first approach, has a limited scope:

- Supply risk is interpreted as present day geopolitical risk only.
- Economic importance is interpreted as the amount of money made by the sectors using the material.

We have applied criticality assessment to a wide variety of materials, including not only elements of the periodic table, but also biobased materials. From these exercises, we concluded that criticality assessment according to this method has limited value in cases of a real concern about the accessibility of materials not just this split second, but for the coming years. Some findings that are unexpected, and possibly unfortunate, are the following:

- Abandoning imports from geopolitically risky countries leads to a lower supply risk, even if there is no way the remaining countries could supply sufficient materials
- A wider use of the material leads to a lower economic importance
- Higher recycling rates do not necessarily lead to a lower supply risk.

We propose to expand the EU criticality assessment to increase its potential by adding a future oriented component for both supply and demand. On the supply side it is essential to include other aspects besides geopolitics, such as geological information and social and environmental aspects. A sensitivity analysis for different assumptions on future geopolitics could also be useful. On the demand side, explorations of the future are essential to capture expectations of steeply rising demand, of resource efficiency, of recycling rates, of the combination of elements in products, and of substitution. In such a way, the assessment gives a better feeling for the real risks involved in the supply of certain materials.

The Role of Reuse in Circular Economy: Quantifying the Spatial Flows of WEEE Reuse in China Based on Network Analysis

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tao Wang [1]***, Xin Tong*** [1]***, Huiting Huang*** [1]

***1.** Peking University*

With the increasing consumption of electronic products, waste electrical and electronic equipment (WEEE) management has become an important issue in China's circular economy. How to divert the flow of WEEE from informal recycling channels with poor environmental risk control is key to the construction of an effective WEEE recycling system. Since 2009, China has built a nationwide formal disposal system for electronic waste disassembly based on the vision of extended producer responsibility (EPR). However, in addition to its potential to pollute the environment, WEEE also has value as resources, such as metals and plastics. The existing fund subsidy system pays more attention to standardizing and controlling the end-of-life disposal processes, focusing on disassembly and material recycling rather than reuse of the products. It also does little to give producers incentives to design eco-friendly and change their business models for sustainable consumption. Therefore, the echelon industrial chain that contains reuse (second-hand market), recycling and dismantling is established by the invisible hand rather than the planning of formal system. In the reuse and recycling process of WEEE, the informal recycling sector has long played an important role due to its flexibility and strong network of connection in the market. In recent years, the emerging Internet recycling platforms have also participated in the value chain of recycling, especially in the reuse process. The spatial flow of the reuse (second-hand) market of WEEE is becoming multidirectional, and a complex network involving multiple spatial scales and process has been formed.

In order to depict the spatial structure of the WEEE flow network more comprehensively, on the premise of estimating the amount of WEEE generated and discarded, this paper adopts network analysis methods, combined with geospatial analysis methods such as spatial autocorrelation and spatial interaction models, to describe the characteristics of WEEE reuse network at the municipal level, identify the important nodes and key flow directions in the recycling chain, and measure the stability of WEEE reuse network.

The results show that (1) under the current WEEE recycling model, the spatial distribution of waste discarding and disassembly has significant regional disparity, which is closely related to factors such as economic development, culture, recycling market and second-hand cascade utilization network. (2) The amount of WEEE discharged by consumers in the Internet recycling platforms is growing rapidly, and there is a trend of diversified competition among platforms, which is more conducive to WEEE resourcing. (3) The network for reuse (second-hand market) has high degree of centers at national level, while the network for disassembly is by far regionalized. By comparing the two-years data, it can be seen that the hierarchical centrality feature is relatively stable, which means that the government can boldly invest in more recycling infrastructure for WEEE reuse and recycling. The national central nodes are strongly connected, while the regional central nodes have seen new changes.

Based on the complexity of the spatial distribution and flow of e-waste, this paper suggests that the government should adopt an innovative way to improve the traceability of products throughout the life-cycle chains, and build a platform for knowledge sharing among multi-stakeholders, especially encouraging the producers to actively be involved in the management of end-of-life stage of their products to improve the life-cycle environmental performance.

What Can Industrial Ecology Learn from Process System Engineering

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Bartolomeus Häussling Löwgren [1]***, Bernhard Steubing*** [2]***, Giuseppe Cardellini*** [3]

1. Institute of Environmental Sciences (CML) Universiteit Leiden, VITO EnergyVille, 2. CML Leiden, 3. VITO EnergyVille, Sustainable Energy for the Built Environment (SEB)

Introduction and objectives

With increasing data, and inter-linkage of rigorous energy, process, and product system models integrated assessment approaches in industrial ecology (IE) need a new set of methodologies to analyze, assess and optimize such large-scale systems. In this presentation novel methodologies from process system engineering (PSE) integrating IE concepts and methods are reviewed and their potential and relevance for integrated assessment methods in industrial ecology are discussed. The goal is to create a dialogue between the fields and give industrial ecologist access to the powerful computational tools developed in PSE.

Methodology

PSE – a scientific discipline integrating scales and components of process or product systems (Pistikopoulos, 2021) – has developed a wide range of methods and software tools called PSE techniques focusing on integrated design, optimization of processes, assessment of alternatives, and optimization in the presence of uncertainty (Grossmann, 2019). For this presentation a systematic literature review is conducted on the published methodologies in PSE integrating IE methods. The methodologies are reviewed with a focus on the system description, problem formulation and underlying objective. Additionally, the implemented tools for modelling, optimization and statistical analysis are discussed. The presentation will focus on the relevance and applicability of these tools and methodologies for large integrated assessment problems in IE.

Results

For the following IE approaches and concepts: attributional-, consequential-, hybrid- life cycle assessment, social assessment, planetary boundaries, environmental extended input-output analysis, and circular economy, novel integrated methodologies have been developed in PSE for large multi-scale systems. This includes novel techniques for multi scale modelling, process design, and optimization. Analyzing the relevance of these techniques for IE problems shows that they can facilitate the integration of large, complex, and interconnected systems, discover trade-offs and bottle necks, prove optimality, and integrating uncertainty at low computational power and relying on mathematical stringency. Further on, it is identified as important that these techniques are reviewed and extended by industrial ecologist. This will lead to correct implementation of IE methods and concepts and more accurate system description. Consequently, limiting misinterpretation of results and green washing.

Conclusion

There are multiple relevant novel methodologies and tools developed in PSE for industrial ecologists working with large scale systems and integrative assessment approaches. Additionally, the importance of industrial ecologist co-developing these methodologies has been shown to limit misinterpretation and green washing.

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On Toast - Environmental Impacts of High-Protein Options for Bread Toppings

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:28: Impacts (short presentations) (B0.16 KOG)

Jessica Bosseaux [1], *Eugene Mohareb* [1], *Cristina Madrid-López* [2]

1. University of Reading, 2. Universitat Autònoma de Barcelona (UAB

Meat production is an important contributor to environmental degradation due to the required resource inputs and their associated climate impact. The reduction in meat consumption and the rise in proportion of people following plant-based diets in the United Kingdom over the last decade is associated with some improvements of environmental emissions and use (Stewart et al., 2021). Nevertheless, this trend must be accelerated towards reaching our collective sustainability targets, such as those highlighted in the EAT-Lancet report (Willett et al., 2019), as well as meeting nutritional expectations and improving public health.

Pulses, particularly beans, are ancestrally consumed due to their climate and disease resilience, nutritional benefits, and ease of storage (Albala, 2017; Popescu & Golubev, 2011). One such pulse is the haricot bean, used in the traditional "beans on toast", which is a common breakfast and snack food in England. Haricot beans, and pulse more broadly, may be a good alternative to other spreadable bread toppings for both the environment and health.

This study investigates the environmental impact of 15 alternatives to beans in tomato sauce that could be considered as a healthy snack and can be spread or deposited on toast. The products have been selected according to their ease to use and their protein content. Serving sizes are also considered to reflect typical practices for their use on bread. Life cycle assessment (LCA) focuses on impacts including water consumption, land use, and global warming potential per serving, using the ReCiPe 2016 midpoint method and the 2020 AGRIBALYSE v 3.1 life cycle inventory. Product flows are revised to reflect UK conditions in place of those in France.

Unsurprisingly, the animal-based products have higher general environmental impacts than plant-based products. Nevertheless, some unexpected results are observed: the four products that had the greatest contribution to climate change are flaked tuna in tomato sauce (0.677 kg CO2 eq/serving), smoked cured ham(0.505 kg CO2 eq/serving), sardine in tomato sauce (0.310 kg CO2 eq/serving) and salmon rillette (0.301 kg CO2 eq/serving), revealing the relatively high impacts of commercial fishing. This is due to diesel combustion in marine engines and the necessary cold chain, including in transport and storage conditions.

Concerning water consumption, peanut butter production (0.0073 m^3/serving) was found to be higher than soft cheese, half of the meat alternatives, and all of the fish alternatives; this is due to irrigation requirements at peanut farms as well as at sugar beet farms, a secondary ingredient in peanut butter. It is followed by flaked tuna in tomato sauce (0.006 m^3/serving) and the traditional haricot beans in tomato sauce (0.006 m^3/serving). Also, land use for peanut butter (0.202 m^2a crop eq/serving) is higher than soft cheese (0.153 m^2a crop eq/serving) but remains lower than all meat-based alternatives. When normalising these impacts based on protein-corrected amino acid score, the order doesn't change substantially, with beans on toast being top of the list.

Haricot beans in tomato sauce shows interesting nutritional benefits as a high source of both carbs and protein, while being low in fat. The volume of the portions is higher and show a better calorie density, which may lead to the use of one single portion of beans, while the high calorie density products such as cheese may lead to the consumption of several recommended portions.

How industrial symbiosis contributes to carbon neutrality strategy and UN SDGs? An Empirical study on Asia-Pacific region

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Liang Dong [1], *(Anthony) Shun Fung Chiu* [2], *Hung-Suck Park* [3]

1. City University of Hong Kong, 2. De La Salle University, 3. University of Ulsan, Korea

Industrial symbiosis and eco-industrial park (EIP) is novel approach to practice circular economy and realize sustainable development goals (SDGs) in park and regional level. Carbon neutrality strategy is highlighted in the post COP-27 era, in which, industrial symbiosis is potentially to play a vital role to contribute the target of net zero society. This study performed as a try to explore how industrial symbiosis performance will contribute to carbon neutrality strategy and UN SDGs, based on the analysis on the causal mechanism between industrial symbiosis and corporate sustainability, and with application of the difference in difference (DID) model and qualitative analysis. In particularly, the benefits of industrial symbiosis to green the whole economic system is evaluated based on input-output analysis. A comparative study was conducted in China, Japan and Korea's EIP programme. Our findings highlighted the significant contribution from industrial symbiosis to carbon neutrality and UN SDGs. Based on the analytical results, how the emerging carbon neutrality toolkit could be applied to boost the industrial symbiosis practices is discussed, and, an integrated toolbox including advanced regulatory tools, market-based tools, financial/fiscal tools, governance tools and commercialization mechanisms is proposed, based on a policy mix analysis on over 200 carbon neutrality related tools in China, Japan and Korea. Our results expect to offer policy support and help to design novel business model, to local and regional industrial symbiosis and EIP practice in the context of carbon neutrality strategy.

Approaches to expand the use of the secondhand product: Analyzing the factors influencing consumer acceptability by product type

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Dami Moon [1], ***Kiyotaka Tahara*** [2], ***Kiyo Kurisu*** [3]

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This study aims to analyze the factors influencing consumer acceptability of the secondhand product considering product type as the fundamental step towards building the use of secondhand products as a general means of consumption towards ensuring sustainable consumption patterns.

A secondhand product generally refers to a product owned by the initial consumer for a certain period of time. Secondhand products tend to be obsoleted or inferior in performance to new ones. Therefore, in the Japanese secondhand market, some items that do not significantly affect their use due to product defects, such as obsolescence, have used to be traded mainly. Moreover, there has been a strong perception that secondhand products are mainly consumed by users, such as low-income people who want to buy them as cheaply as possible or people who collect old items as a hobby. The recent emergence of online flea market applications has allowed users to trade various secondhand products directly among consumers. These market changes can trigger a shift in consumer awareness of the consumption of secondhand products. Based on this current situation, this study focuses on promoting the use of various types of secondhand products by a broader range of users to recognize as one of the significant means of consumption. In particular, this study confirmed the difference in the current usage of secondhand products considering product type by investigating product acquisition modes of various household items. Moreover, the factors influencing consumer acceptance of the use of the secondhand product by product type are also investigated. Here, the use of the secondhand product was examined from the two perspectives: acquisition and transfer.

As a methodology, two questionnaire surveys (implemented in 2021 and 2023) were carried out, targeting Japanese residents. In a survey conducted in 2021, the ratio of Japanese respondents' secondhand product acquisition experiences for daily necessities and convenience goods was low (4.6%-9.0%), while the ratio of the acquisition experience for some hobbies used irregularly was high (27.9%-38.0%) compared to other product types. Based on these findings, analyzing factors affecting the promotion of consumer behavior in acquiring and transferring secondhand products considering product types is left as future work. In addition, the difference in secondhand product acceptance factors between experienced and inexperienced users of secondhand products will be analyzed to examine the directions to widen the range of secondhand product consumers. These results can help suggest concrete approaches to expand the use of secondhand products in the context of implementing sustainable consumption behavior.

The study is the result of Value Exchange Engineering research conducted in collaboration between R4D, Mercari, Inc. and RIISE.

Progress in Eco-Industrial and Circular Business Parks: Updated framework and cases from the Netherlands

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jaco Quist [1]***, Carlos Valladolid*** [1]***, Gijsbert Korevaar*** [2]***, Geerten van der Kaa*** [1]

1. *TU Delft*, ***2.*** *Technical University Delft*

To transition to a circular economy, eco-industrial parks (EIPs) and Circular Business Parks (CBP) are needed. However, developing EIPs and CBPs is complicated. Nevertheless, some EIPs that are successful with industrial symbiosis and utility sharing activities happening. For instance, there are only few case on EIPs and CBPs in the Netherlands reported. Therefore, the progress on EIP and emergence of CBP in the Netherlands is addressed in this paper asking: "How to facilitate the implementation of industrial symbiosis and utility sharing activities in EIPs in the Netherlands? To answer this question, the factors for the success of industrial symbiosis and utility sharing in EIPs were identified through the literature review to update the framework of Eilering & Vermeulen (2004). Three new factors were added, leading to ten factors important to implement industrial symbiosis and utility sharing when developing an EIP or CBP. The factors are: (1) vision and ambition, (2) location-specific physical features, (3) location-social specific features, (4) business-specific features, (5) proposed measures, (6) organisation of decision-making, (7) policy instruments, (8) economic features, (9) external context, and (10) serendipity.

The refined framework was applied to three successful parks in terms of industrial symbiosis and utility sharing: InnoFase in Duiven, Industrial Park Kleefse Waard in Arnhem, and Biopark Terneuzen in Zealand. Data collection took place via semi-structured interviews with respondents for each case study. Findings show that industrial symbiosis and utility sharing activities could be identified at all three parks. InnoFase is engaged in many industrial symbiosis activities by exchanging different types of flows such as biomass, biogas, water, electricity and heat, while other synergies are ;under development. At IPKW mainly utility sharing activities were found, including a gas-fired power plant fed by the on-site wastewater treatment plant. Other smaller flow exchange activities include plastic, biomass, and wood reuse by some of the companies. The case of Biopark Terneuzen revealed that the exchange of flows ass typically used in the literature is not accurate because some intended exchanges never materialized. A cross-case analysis was conducted to identify what sub-factors or barriers were present in every case. In total, 63 sub-factors could be identified that influenced the success of the park. It is concluded that social innovation is key to implementing industrial symbiosis and utility sharing.

Testing multiple policies for organic waste separation at SMEs in cities using collaborative agent-based modelling

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Kasper Lange [1]***, Sabine Kerssens*** [2]***, Gijsbert Korevaar*** [2]***, Martijn Warnier*** [2]

1. *Amsterdam University of Applied Sciences,* ***2.*** *Technical University Delft*

This research contributes to understanding and shaping systems for OFMSW separation at urban Small and Medium Enterprises (SMEs, such as offices, shops and service providers). Separating SMEs' organic fraction of municipal solid waste (OFMSW) is both an opportunity and a serious challenge for the transition towards circular cities. It is an opportunity because OFMSW represents approximately 40% of the total waste mass generated by these companies. It is challenging because post-collection separation is not feasible for OFMSW. Therefore, SMEs disposing of waste should separate their solid waste so that processing the organic fraction for reuse and recycling is practical and attainable. However, these companies do not experience direct advantages from the extra efforts in separating waste, and much of the OFMSW ends up in landfills, often resulting in unnecessary GHG emissions. Therefore, governments and waste processors are looking for ways to improve the OFMSW separation degree by urban companies disposing of waste through policies for behaviour change.

There are multiple types of personnel at companies disposing of waste. These co-workers act according to their values, beliefs and norms. They adapt their behaviour continuously, influenced by the physical environment, events over time and self-evaluation of their actions. Therefore, waste separation at companies can be regarded as a Socio-Technical Complex Adaptive System (STCAS). Agent-based modelling and simulation are powerful methods to help understand STCAS. Consequently, we have created an agent-based model representing the evolution of behaviour regarding waste separation at companies in the urban environment. The model aims to show public and private stakeholders involved in solid waste collection, transport and processing to what extent behaviour change policies can shape the system towards desired waste separation degrees.

We have co-created the model with participants utilising literature and empirical data from a case study on the transition of the waste collection system of a business park located at a former harbour area in Amsterdam, The Netherlands. First, a conceptual model of the system and the environment was set up through participatory workshops, surveys and interviews with stakeholders, domain experts and relevant actors. Together with our case participants, five policies that affect waste separation behaviour were included in the model. To model the behaviour of each company worker's values, beliefs and norms during the separation and disposal of OFMSW, we have used the Value-Belief-Norm (VBN) Theory by Stern et al. (1999). We have collected data on waste collection behaviour and separation rates through interviews, workshops and a literature study to operationalise and validate the model.

Simulation results show how combinations of behaviour profiles affect waste separation rates. Furthermore, findings show that single waste separation policies are often limitedly capable of changing the behaviour in the system. Rather, a combination of information and communication policies is needed to improve the separation of OFMSW, i.e., dissemination of a newsletter, providing personal feedback to the co-workers disposing of waste, and sharing information on the (improvement of) recycling rates.

This study contributes to a better understanding of how policies can support co-workers' pro-environmental behaviour for organic waste separation rates at SMEs. Thus, it shows policymakers how to stimulate the circular transition by actively engaging co-workers' waste separation behaviour at SMEs. Future work will extend the model's purpose by including households and policies supporting separating multiple waste types aimed at various R-strategies proposed by Potting et al. (2016).

The Short-Term Impact of Air Pollution on Healthcare Expenditures

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

haofan zhang [1], ***dianyu zhu*** [1], ***pan He*** [2], ***Miaomiao Liu*** [1], ***Jun Bi*** [1]

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Understanding the health impact of air pollution is critical for understanding the benefit of environmental regulations, especially under the synergies of carbon neutrality and air pollution control. We examine the effect of fine particulate matter (PM2.5) on individual healthcare expenditures in China from 2017 to 2019 using daily transaction data from 320 cities and evaluate the health co-benefits of carbon neutrality. Results show that each 10 μg/m3 increase in daily PM2.5 exposure is associated with a 0.31 percent increase in three-day healthcare consumption and a 0.53 percent increase in three-day individual healthcare expenses. Achieving carbon neutrality goals with the national air quality daily standard of 35 μg/m3 can save 1.5 billion yuan annually. Ambitious goals with World Health Organization Air Quality Guidelines of 15 μg/m3 can nearly double the saving. This study not only provides insight into the potential health benefits of carbon neutrality in China but also suggests that extensive benefits may result from more ambitious targets.

Navigating China's Cement Production Landscape: A Benchmark Analysis of Carbon Emissions

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jing Guo [1], *Jianchuan Qi* [1], *Nan Li* [1], *Ming Xu* [2]
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As global concern for the environment increases, there is a growing demand for low carbon and sustainable products and services. Life cycle assessment (LCA) is a widely-used tool for evaluating the environmental impact of products and services. However, traditional LCA approaches can be time-consuming and resource-intensive, especially when improving the sustainability of complex industrial processes because it involves the analysis of a complex network of interrelated processes, materials, and environmental impacts which requires multiple-sourced and dynamic data.

Knowledge graph (KG) can help solve these challenges by providing a structured and connected representation for managing complex knowledge, including relationships and interconnections between entities. Incorporating LCA into a knowledge graph offers opportunities to make strategic recommendations based on a deep understanding of the industrial process and its components.

We propose a KG-based approach to intelligent strategic recommendation toward low carbon industrial design. Based on the knowledge graph that represents the relationships and interconnections between different industrial processes, inputs, and outputs, as well as the associated environmental impact data, various techniques, including link prediction, graph clustering, pathfinding, etc., are integrated in our approach. Link prediction enables us to identify potential new low carbon industrial processes that have not yet been explored, as well as to make recommendations about how existing industrial processes can be optimized to reduce their environmental impact. Graph clustering can be used to identify similar stages in the life cycle of a product or process in the LCA KG. Pathfinding could identify the shortest paths between entities in the LCA KG to determine the most efficient, effective and sustainable routes. These techniques are used in combination to provide a comprehensive and informed approach to strategy recommendation using a KG.

In order to evaluate our approach, we conducted a case study of a cement production process optimization, incorporating data from multiple sources and representing it in a knowledge graph for intelligent suggestion. The effectiveness of our approach in recommending low carbon industrial processes will be discussed and demonstrated, which highly possibly becomes a promising solution to the challenge of reducing the environmental impact of industrial activities.

Towards a Circular Built Environment: wasteful construction and demolition practices and how to overcome them

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Mario Kolkwitz [1]

1. *Tampere University*

Buildings and materials are valuable, yet underutilized reserves of space and secondary resources embedded within the urban built environment. To reach global sustainability goals, the principles of circular economy (CE) are a promising countermodel to current linear waste practices by utilizing the resource potentials of the existing building and material stocks.

The main research subjects of this doctoral dissertation are the Finnish cities of Tampere and Vantaa. In the first part of this dissertation, the focus lies on the cities' building stocks, construction, and demolition. The study's methodological framework is Urban Metabolism (UM) which is defined as the in- and outflows of materials and energy, their respective stocks as well as the internal processes which generate and shape them (Baccini and Brunner, 2012). Due to the absence of material indicators for the Finnish building stock (Pesu et al., 2020), the research focus at this earlier stage lies on buildings as such. Despite this unconventional approach, the study method can be described as a Material Flow Analysis which is defined as the analysis of flows of materials (and products) as a balance of in- and outflows and their impact on a stock (Brunner and Rechberger, 2004). Through a statistical and spatiotemporal analysis of Tampere's and Vantaa's building stocks, in- and outflows in form of construction and demolition between 2000 and 2018 the aim is to get deeper insights into patterns and drivers within their UMs.

One notable contribution of this dissertation will be the creation of material indicators for parts of the Finnish building stock which will be combined with findings from the aforementioned study of building stocks and flows. The analysis of material contents links patterns in urban spatial and temporal development with their carbon, hence environmental consequences. The outcomes are expected to inform stakeholders from throughout the building industry and policy-making about the negative impacts of current business-as-usual practices and to redirect towards an approach that focuses on maintenance and transformation.

The final part of this dissertation investigates how the natural adaptation potential of the whole Finnish building stock could be utilized to extend building hence, material life cycles. The research method encompasses a statistical and geographical investigation of buildings throughout Finland that have changed their function between 2014 and 2018 in order to identify building types and properties that favour transformation over demolition. Evidence from buildings with a high transformation capacity will be compared with the preceding research on demolition patterns to identify the potential of building adaptation to mitigate material and waste streams. Furthermore, this research will show archetypes that lack the natural transformation capacity which will call for follow-up research that studies the architectural and other internal and external factors impacting the transformation capacity of buildings.

This dissertation sets out to create a foundation for understanding the dynamics within the Finnish building stock. The goals are to find environmentally harmful construction and demolition practices, to identify the natural transformation capacity of buildings, and – with this in mind – to define the most impactful application areas for the implementation of CE strategies.

This dissertation is largely funded by the collaborative Horizon 2020 project CIRCuIT (Circular Construction in Regenerative Cities). For its finalization, this dissertation was awarded a one-year grant by the Finnish foundation Kaute-säätiö.

Raw materials, global supply chains and local systems in an eco-industrial perspective. A case study from the wood industry

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Raffaella Taddeo [1]***, Alberto Simboli*** [1]***, Veronica Casolani*** [1]***, Giuseppe Ioppolo*** [2]

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In recent years, temporary events such as natural disasters, logistical problems, socio-political and pandemic crisis, as well as structural trends, such as the globalization of supply chains and the depletion of mining and extraction sites, have affected the availability and prices of many raw materials. In addition, the return effects of the progressive diffusion of sustainable and circular practices within economic systems, e.g. the dynamics of substitution related to the use of renewable materials and/or secondary raw materials, are influencing the behaviour of the actors and the operating rules of the intermediate and final markets.

The synergistic action of these forces can lead to a revision of the organization and functioning of entire supply chains, creating spaces and possibilities for their sustainable transition based on approaches focused on proximity and territoriality, primarily, among these, those based on Industrial Ecology.

The wood industry and wood-based materials, historically, represents one of the main sources of industrial input for many supply chains, thanks to its possible direct and indirect uses in many industries (e.g. construction, furniture, logistics, paper, heating). Wood is also one of the most significant materials in terms of sustainability, mostly considering the environmental and social effects of an uncontrolled supply of raw materials (e.g. deforestation, climate change, loss of biodiversity, balance of hydro-geological systems).

Italy is particularly interested in improving the efficiency of its wood industry and supply chain. In fact, despite the Italian woodland and forest areas have progressively increased, the harvesting rates are among the lowest in Europe, and it is getting harder to satisfy the internal demand; this means that over 80% of the primary wood used in Italy is imported. The instability of prices and the scarcity of raw materials that has recently affected the wood industry, together with the Italian industrial structure, strongly characterized by the presence of local production settlements, make it particularly interesting to investigate this sector and the related materials for its potential local eco-industrial development.

The research presents a case study carried out at a regional level, in which the availability of local resources, the companies and supply chains currently settled, the potential for applying circular practices in the supply chain and the possible eco-industrial interactions are considered.

The results demonstrate how even currently linear supply chains can find new possibilities for a circular and eco-industrial development, and how these kind of solutions can provide companies with new tools to deal with temporary and structural criticalities and increasing the synergies and resilience of the local systems in which they are placed.

When is repair environmentally beneficial? The case of high-voltage electric motors

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Use extension by repair is a circular economy (CE) strategy that has been advocated to improve products' environmental performance and resource efficiency. Previous studies have shown that this does not necessarily hold for energy-using products, for instance, when a more energy-efficient product is available for replacement. The requirements for use extension to be beneficial have been found to vary with the product and its use conditions. However, resource depletion is seldom discussed, and the case of very long-lived and energy-intensive products has not been addressed yet.

An example of such an energy-intensive product is high-voltage (HV) electric motors, typically used for more than 20 years and in operation for 50 weeks a year full time. Electric motors represent 50% of the electricity consumption in Europe and despite being few, HV motors represent a significant share of this consumption. The two HV motor designs, induction motors (IM) and synchronous motors (SM), are often used until failure, commonly occurring in stator windings which could be repaired but with the risk of affecting energy efficiency. This work aims to provide recommendations on important aspects for use extension to be environmentally beneficial for long-lived and energy-intensive products.

Cradle-to-grave LCAs are performed for global warming and mineral resource depletion to compare (1) the two motor designs and (2) each motor with and without use extension through repair. The motors are chosen to deliver the same output of 16 MW and the functional unit is set to one year of operation. The IM has an energy efficiency of 97.3%, the SM has an efficiency of 98.3% and both are operated for 20 years. The additional use time and the efficiency reduction after the repair are left as varying parameters between 1 and 20 years and between 0 and 1% respectively.

Results show that, due to high energy use and long lifetime, the impact of electricity use during motor use is dominant for both global warming and resource depletion. This dominance remains with different electricity mixes, including in a scenario with hydroelectricity only. For resource depletion, it is due to copper in transmission lines and resources for electricity production (e.g., uranium from nuclear energy production). The dominance of the use phase results in energy efficiency being key to the environmental performance of HV motors. The more efficient design, the SM, results in lower impacts than the IM in both impact categories. In terms of resource depletion, SM manufacturing is more impactful but lower energy losses during use compensate for the difference. Besides, additional energy losses from a small energy efficiency reduction offset the gain from the repair for both global warming and resource depletion. The gain from the use extension by repair is small compared to the benefit of choosing the more efficient design.

Choosing and maintaining high energy efficiency is key for long-lived and energy-intensive products' environmental performance due to their high energy requirements and long lifetime. Thus, efforts should be channelled on ensuring high energy efficiency by design and after repair. This is relevant for both policy-making and manufacturers or users when prioritising strategies for improving products' environmental performance. Finally, as conclusions are similar for global warming and resource depletion, this work demonstrates the importance of including resource use from electricity production and transmission when exploring the use extension of energy-using products.

Methodology for evaluating the circular use of secondary steel resources under the current steel consumption pattern

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Han Gao [1]***, Ichiro Daigo*** [1]

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Steel recycling contributes to both retarding iron ore mining and GHG abatement. The consumption of steel scrap varies among countries due to the differences in availability and economic factors of materials and the facility of steel production. Steel scrap differs from pig iron or Direct reduction iron because of its high contents of tramp elements and the uncertainty of those contents. High impurity contents in steel scrap can restrict the consumption of scrap and weaken the willingness to scrap recycling. In order to promote steel recycling and identify the higher potential demand for scrap, modeling how the primary and secondary steels are embedded in steel flows is critical as it unveils how much steel scraps are contained in products and the destination of steel scrap. In this study, we aim to develop an evaluation methodology for the circular use pattern of secondary resources under its current resource consumption pattern.

First, we developed the framework of the consumption pattern analysis of primary and secondary resources with seven layers, representing resource extraction to end uses. Applying this framework to a case, we constructed a multiregional material flow model with a Physical Supply and Use Table of iron and steel covering 25 countries in 2017. Then, we adopted the Leontief model to calculate the total input coefficients of steel scrap, representing the portion of steel scrap in the total resource input of iron and steel resources. The long steel could consume more steel scrap which is regarded as low quality, and the flat steel could consume less steel scrap which is regarded as high quality. Using this criterion for steel quality grades, we analyzed the steel scrap content (SSC) of steel products and end uses. Finally, we made an international comparison of characteristics of circular use patterns through SSC of products and end-use sectors.

The results of the SSCs of flat and long steel in 25 countries show numerical evidence for the designated criterion. The study indicates that the high SSC of long steel products in the US, Finland, Sweden, Canada, Mexico, and India could be 85-90%, while the SSC of flat steel products is 19% in all countries. The results of SSCs of ten end-use sectors of all countries display that the construction, motor vehicle, and machinery sector were the top three destinations of total embedded steel scrap due to the large consumption of scrap-based long steel products. In contrast, end-users of electrical machinery, furniture, and other manufactured goods completely relied on ore-based flat steel. The proposed framework has been effective in identifying consumption patterns of primary and secondary steel and could help promote steel scrap recycling with the provision of SSCs of steel products of any economy.

Comprehensive management of excavated soil and rock: A material flow analysis in Shenzhen, China

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hongzhou WANG [1]

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China has been experiencing rapid urbanization, resulting in intensive construction activities. Accordingly, massive excavated soil and rock (ESR) have been generated and disposed of yearly, which is detrimental to the natural environment and induces geological disasters. However, current research is insufficient to characterize the ESR compared to other construction and demolition waste. Therefore, this study aims to use Shenzhen, a fast-growing megacity in China, as an example to quantify the generation and flows of ESR. Data was collected from official documents and field investigations between 2015 and 2021. The results indicate that more than 80 million m3 of ESR was generated in Shenzhen annually, primarily from building and rail transit construction projects. Approximately 72% of ESR was transported and traded with other neighboring cities. Meanwhile, recycling activities have digested a minor amount of ESR, with a low weight fraction below 10%. The findings suggest the significance of ESR minimization and recycling in reducing environmental risks. Regional collaboration is also crucial between the cities in the Pearl River Delta to optimize cross-jurisdictional ESR trading. Overall, this research offers references to enhance environmentally sound management of ESR in Shenzhen, which may also be applied to other Chinese cities.

Evaluating resource use reduction effects of residence-related circular economy actions; differences among housing structures and regions

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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The current linear economy involves mass production, mass consumption, and mass disposal. In recent years, government policies such as the Circular Economy Action Plan in EU and Circular Economy Vision 2020 in Japan have emphasized a transition to a circular economy. Consumers and producers must engage in circular economic actions and adopt reduce, reuse, and recycle principles (3Rs).

The housing construction sector is among the largest resource-consuming sectors. Understanding how the 3Rs are applicable to the sector is fundamentally important for implementing circular economy policies. We proposed a structural decomposition of the natural resource use intensity of housing, defined as the amount of natural resource used per housing resident. For decomposition analysis, six terms were assessed: floor area per housing resident, housing occupancy rate, house useful lifetime, intensity of construction material use, production efficiency of construction materials, and the percentages of recycled materials used to produce construction materials. The analysis examines wooden houses, which are often traditional houses, and non-wooden houses, including those of reinforced concrete and steel reinforced concrete structures, used particularly in apartment buildings. This study examined three Japanese prefectures with representative climate conditions: Hokkaido as a cold zone, Tokyo as a temperate zone, and Okinawa for its subtropical conditions.

Our results show that the resource intensity of non-wooden houses was 4.6 higher than that of wooden houses in 1988, but the difference decreased to 1.3 times in 2018 because of increased non-wooden houses' useful lifetime and the use of recycled materials. This evolution was similar for the three prefectures studied. Although the resource intensity of wooden houses was low in Hokkaido and Tokyo, Hokkaido had a larger floor area and used fewer materials for new construction. In terms of non-wooden houses, Okinawa consumed more raw materials per capita because buildings there require durability against typhoon winds. An increasing floor area per housing resident is one factor that expanded resource consumption in Okinawa and Tokyo. Results for all prefectures showed that the increased floor area per housing resident increased resource use, while the use of natural resources decreased because of the extension of houses' useful lifetime.

Hierarchical Bayesian analysis of consumer preferences for data-driven agent-based simulation of Circular Economy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ryu Koide [1]***, Haruhisa Yamamoto*** [2]***, Koji Kimita*** [3]***, Nariaki Nishino*** [3]***, Keisuke Nansai*** [2]***, Shinsuke Murakami*** [3]

1. *Material Cycles Division, National Institute for Environmental Studies,* ***2.*** *National Institute for Environmental Studies,* ***3.*** *The University of Tokyo*

A transition to the Circular Economy (CE) is expected to contribute to environmental sustainability, but its diffusion potential and environmental performance largely depend on consumer behaviors. However, empirical analysis of consumer behaviors in CE considering their heterogeneity has been scarce in the existing literature. There are several behavioral determinants of the diffusion of CE and its system-wide consequences: i) consumer preference for acquisition, repair, and discharge of products, ii) product obsolescence due to failure and other reasons, and iii) dissemination of information and social utility through a social network. In this study, we applied hierarchical Bayes methods to estimate determinants of heterogeneous consumer behaviors based on a consumer survey using a case study of home appliances.
The data used in the study was from a large-scale consumer survey of a nationally representative sample in Japan, which consisted of questions on choice experiments, product lifetime, and communication regarding three types of CE business models (reuse, refurbishment, and subscription service) of home appliances. First, the hierarchical Bayes choice-based conjoint analysis estimated part-worth utilities of the product acquisition, repair, and discharge. The analysis of product acquisition revealed that new CE business models, i.e., refurbishment and subscription service, can increase consumer acceptance of circular products compared to traditional reuse. Consensus clustering of the estimated individual-level part-worth utilities revealed four consumer segments: i) subscription-prone, ii) price-sensitive, iii) balanced decision-maker, and iv) brand-new stubborn segments. Segment-wise potential market shares were predicted, concluding that the circular business models can obtain a market share of up to approximately 35% due to potential cannibalization (competition) between circular business models. The cross-analysis with the composition of awareness and consideration sets revealed that this share could be as lower as about 10% because consumers only sometimes consider all available alternatives in the market due to bounded rationality. Analysis of repair and discharge choice identified important service design factors for attracting consumers to participate in CE, such as repair costs, delivery time, and transparency on the destination of collected products. In addition, product use period and reasons for obsolescence were analyzed by i) two-step models of parts failure and troubles and ii) proportional hazard survival model considering household characteristics. Approximately half of product use termination was due to reasons other than failure. Some particular consumers, such as high-income, small-sized families, and younger households, tend to have shorter product use periods. Other CE-related determinants of consumer behavior and product use, such as impacts of word of mouth and social utility (homophily), were empirically analyzed, concluding the significant roles of awareness, social network, and communication in determining consumer behaviors in CE.
The estimated consumer behavior determinants were used to calibrate the agent-based model for simulating consumer behavior and product circulation in CE for assessing circularity and environmental consequences, which some of the authors had developed. Here, the Data to Agents Mapping and synthetic population considering heterogeneous consumer preference, probability of product obsolescence, and social network topology were developed. This presentation overviews the methodology for using empirical data to calibrate agent-based simulation, with some preliminary simulation results. The empirical survey analysis provides a valuable understanding of the determinants of consumer behaviors in CE and empirical grounding for agent-based simulation

to support early decision-making to identify effective policies and business decisions for realizing the transition to CE.

Meta-analysis on greenhouse gas emission reduction potentials, backfire effects, and assessment methods of circular economy strategies

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ryu Koide [1], ***Shinsuke Murakami*** [2], ***Keisuke Nansai*** [3]

1. Material Cycles Division, National Institute for Environmental Studies, 2. The University of Tokyo, 3. National Institute for Environmental Studies

An introduction of circular economy strategies and product-service systems, such as rental, sharing, and refurbishing, is expected to reduce environmental impacts. Still, there have been mixed findings on its consequences due to potential rebound and backfire effects. In addition, applying LCA to product-service systems faces significant methodological challenges due to system-wide changes in the use phase behaviors and service provision. Although numerous case studies have been published, except for some qualitative or product-specific reviews, there has been no cross-cutting meta-analysis focusing on the environmental consequences of product-service systems. This study conducted a systematic literature review on the greenhouse gas (GHG) reduction potentials of ten different circular economy strategies and assessment methods on consumer durables. Over 1,000 published academic papers were screened from Web of Science and Scopus databases. More than 100 papers with 1,500 scenarios that quantitatively evaluated the life cycle impacts of product-service systems were collected. Products covered by the review were durable and semi-durable consumer goods such as home appliances, information and communication equipment, transportation equipment, and clothing. Target circular economy strategies cover ten types: e.g., servitization, rental, leasing, sharing, reuse, repair, and refurbishment.

The meta-analysis revealed that the expected GHG reductions and the risk of backfire effects varied significantly by circular economy strategies. The results of the cross-cutting analysis of all product types indicated that relatively robust GHG emission reductions (limited risks of backfire effects) were expected from pooling, upgrading, refurbishing, and repair strategies. On the other hand, sharing, reuse, and servitization may have medium to high emission reductions, but their risk of backfiring effects is relatively high (as many as 10-20% of reported scenarios showed emission increases). Several potential factors determining backfire effects in the circular economy were identified: e.g., transportation, frequency of use and user behavior, product lifetime, maintenance, energy efficiency, and product substitution (type and amount of products substituted by newly introduced strategy).

The review of the application of assessment methods in the published papers revealed the need for methodological development of assessing the consequences of multiple circular economy strategies, incorporating the use-phase behavior and dynamic stock models based on empirical data. Most reviewed papers considered only a single strategy rather than their comparison or integration. They were based on attributional LCA methods that focused on comparing typical cases rather than assessing the consequential impacts on the whole society. About one-third of the literature relies on assumptions for data on use, transportation, and disposal phases rather than based on empirical data. Furthermore, sensitivity analysis on functional units was only conducted in less than 5% of the literature, although its choice significantly relates to the identified determinants of backfire effects.

This review study is a first of its kind covering a variety of circular economy strategies and product types, and quantitatively analyzed the current scientific understanding of the environmental consequences and potential backfire effects of product-service systems. The review result calls for more strategic efforts to avoid backfire effects through better service design and consumer behavior change and to promote circular economy strategies with lower backfire risks and robust GHG reduction effects. It also revealed the necessity to develop methods for consequential LCA of circular economy considering product substitution, use-phase behavior, and utilizing empirical behavioral data.

Handprint assessment: measurement of the positive impact to sustainability. The case for cotton.

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Mariana Ortega [1], ***Lise Laurin*** [1]
1. *Earth Shift Global*

A case study on handprints for the cotton sector evaluates how cotton and its co-products affect the environmental and social spheres they touch. Using a screening level Sustainability Return of Investment (S-ROI)[1] approach, risks, and opportunities of global cotton production and use were identified and prioritized. A set of 20 indicators related to climate change, child labor, automation, residue valorization, and traceability among others were estimated either in monetary terms or by the number of people involved. All were analyzed in relation to the UN Sustainability Goals 2030 agenda.
It was found cotton's most immediately pressing risks and therefore opportunities for improvement are in the social dimension. In some cases, the order of magnitude of risks is comparable to potential benefits. Tradeoffs were also identified; for example, jobs will be lost to automation in the midterm future, and this may be compensated to some extent by new job opening through increased cotton co-product valorization strategies. The more that other cotton plant products, such as seed oil and linters, are used, the better the economic results for the cotton farmers and for the environment. A recent LCA study showed a switch in French fries frying oil could lead to savings in greenhouse gas emissions because refined cotton seed oil can reduce climate change impacts by up to 83% in comparison to soybean oil.
Overall, it is shown that by analyzing an agricultural sector as a system through a handprint study, companies could be inspired to look broader and even backcast for more sustainable development.
[1] Developed out of the AIChE Total Cost Assessment Methodology

A timber flow analysis for the UK

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Chi Zhang [1]***, Stijn van Ewijk*** [1]***, Julia Stegemann*** [1]

1. University College London

Timber is an essential resource, which is not only used in the construction industry but also for packaging, furniture, and paper. Since timber has significant potential for carbon sequestration, its use can be an essential strategy for achieving net zero. The benefits of timber are greatest when it is used efficiently in the context of a circular economy, with cascading use at the highest possible value.The UK is one of the largest consumers of timber and panel products in the world, the world's second largest importer of wood after China (FAO, 2022). It harvested 11.2 million m^3 roundwood in 2021, and produced 3.6 million m^3 sawnwood (8% increased from 2020), 3.5 million m^3 wood-based panel (18% increased from 2020), and 3.6 million m^3 paper and cardboard (Forest Statistics, 2022). Moreover, in 2021 it imported 8.5 million pounds wood products, including 8.2 million m^3 sawnwood (13% increase from 2020),3.8 million m^3 wood-based panel (16% increased from 2020) (Forest Statistics, 2022). In additional, no institution, organisation or academic has calculated the recycling rate of wood in the UK, but according to this research's calculation, the wood recycling rate in the UK is approximately 34%. Because of the large market demand, low recycling rate, and high dependence on imports, UK timber industry is in urgent need of sustainable transformation, and how policies can help it improve presents a worth-discussing case study.

Previous studies have explored timber flows in Norway, France, Swiss, and China. In the UK, an accurate and mass-balanced timber material flow analysis (MFA) remain to be studied. Moreover, a timber MFA for the UK is needed to develop policy scenarios to improve timber use efficiency and waste recycling.

The MFA encompasses the various stages involved in forest products' life cycle, including harvesting, manufacturing, usage, waste collection, recycling, reuse, and recovery. The product categories include various types of paper and timber products. Trade of intermediate and final products is part of the material balance. Stocks of timber in buildings are estimated using the material intensity method and the extrapolation of national housing data and construction and demolition case studies.

The MFA represents the implementation of the first part of a dynamic model that will not only describe material stocks and flows but include parameters that capture the effect of decision-making. The application of the modeling approach to timber in the UK will illustrate the method, which is intended to provide a template for decision-relevant MFA for other materials and jurisdictions.

The MFA provides the first analysis of timber flows in the UK that includes an estimate of timber stocks, as well as the end-of-life treatment and destinations of waste flows. The preliminary result suggests that the UK's timber industry strongly relies on imports in the context of counter-globalization, which could prove an additional driver for increased domestic reuse and recycling, besides the potential environmental benefits. The research will provide the basis for assessing the potential for cascaded utilization of timber resources, as well as the decision-making required to exploit this potential for the longer-term use of timber resources.

Economic and environmental performance of residential building envelopes in Israel

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Buildings are responsible for 39% of all carbon emissions in the world. Operational emissions constituting 28% while the remaining 11% come from “embodied” carbon emissions, which are related to materials and construction processes throughout the life cycle of the building.

The study examined from a life cycle perspective the energy performance, environmental and economic impacts of the envelopes of residential buildings in Israel, which include the background wall, insulation, and cladding of the building. We included a comparison between different wall sections, common and less common types as well as more advanced and “green” walls in low and high-rise buildings.

In the first stage, an advanced energy model was performed using dedicated software (Design Builder) to estimate the operational energy for the different designs. Then the model results were used in the LCA tool to further understand the environmental impacts. For each section, the energy consumption, energy rating, and environmental effects resulting from the operational energy and the embodied energy were obtained, when a comparison was also made between the different costs of the walls.

We found that advanced envelopes achieve better energy and environmental performance than their conventional counterparts. The Hempcrete block, CLT, exterior gypsum boards, and ventilated facades presented the best performance, especially in the environmental aspect (GWP and the rest of the categories), but their initial costs were higher. In terms of energy and electricity savings, the gaps were lower, although their overall thermal conductivity was significantly better (2 - 3 times). The economic savings gap reached up to tens of thousands of shekels over 60 years. Polyesh insulation (cement board with EPS) has been found to have the greatest inherent energy. In the field of cladding, natural stone is with the lowest embedded energy compared to industrial claddings, of which Alcobond led with the highest embedded energy in the other environmental categories. The transport part and the end of life of the materials were found to be marginal and accounted for 1-2% of the total embedded energy.

The study has been a milestone in the green building community and for the ministry of environmental protection in Israel, creating incentives for the sector to generate EPDs and adopt life cycle thinking.

Environmental impacts of biochar production and usage: A review

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Antônio Fonseca [1]***, Ana Cláudia Dias*** [1]***, Luís Tarelho*** [1]

1. *University of Aveiro*

The increase in world energy production has intensified major environmental problems, particularly in relation to climate change. Even with the increase in exploring renewable sources of energy, greenhouse gas emissions to the atmosphere keep rising. In this context, biochar has been emerging as a potential solution to contribute to the mitigation of this problem, namely questions regarding the carbon balance and carbon sequestration. Biochar is a solid carbonaceous material produced mainly through the pyrolysis of biomass and has attractive properties such as carbon fixation in soil, water retention, and improvement of soil quality. To evaluate the potential environmental impacts of the production and application of biochar in soil, Life Cycle Assessment (LCA) is a tool being vastly used worldwide.

The objective of this study is to carry out a review aiming to gather information from scientific papers, that use the LCA methodology, to address the environmental analysis of the production and application of biochar. The main focus of this systematic review is to identify the main methodological choices selected to quantify the carbon storage in soil, and the potential environmental benefits regarding the reduction in the use of fertilizers, water, and energy.

To conduct this study, some different variables were analyzed. Firstly, the geographical data and the scale where the studies have been developed. The operation conditions of the pyrolysis process were also analyzed, such as type of reactor used, temperature of the pyrolysis, residence time of biomass, and the percentage of biochar produced from the biomass used. Information about the type of biomass and the reasons behind its choice was also collected.

The LCA methodological aspects of those studies were also gathered such as the system boundaries, the functional unit, the data sources (literature and theoretical data and/or experimental data), the impact assessment method, and the impact categories selected. Those variables will change the potential environmental impacts of the process studied, and for this reason, must be harmonized to allow comparison of results.

Finally, methodological aspects and assumptions related to the application of the biochar in soil were identified focusing on: the percentage of carbon stored in soil, the period of time that this carbon is considered stable, the biochar application rate, and if there is any other consideration regarding the benefits of the biochar application (reduction in fertilizers used, reduction in energy and water for irrigation, increase in crop production).

There is a lot of potential in biochar for carbon sequestration and soil improvement, and the increase in biochar production and usage in the last years in this scope has been growing. However, there is no consensus about the real balance between the impacts and benefits of the production and, especially, the application of biochar in soil. Thus, there is a need for the development of decision-support tools on environmental impacts to support or redirect this strategy.

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Revealing the hidden potentials of IoT - An integrated approach using agent-based modelling and system dynamics to assess sustainable supply chain performance

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Suiting Ding [1]

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The Internet of Things (IoT) brings new opportunities for creating intelligent and streamlined supply chains that have better environmental and cost performance as compared to conventional ones. In this paper, we quantify such improvements for a specific logistics chain case. In particular, we assess the difference in carbon emissions, cost, and market performance of a battery delivery chain in the delivery process between a two-tier IoT-supported supply chain (users are served by an IoT retailer directly connected to the producer) and a conventional three-tier supply chain (producer, wholesaler, and retailer). IoT supported supply chains have much more radical zero-inventory and shipment strategies due to punctual and accurate information transmission, and wholesalers have been replaced by manufacturers directly connecting with retailers. To support the inventory of cost and emission data, we utilize system dynamics (SD) and agent-based modeling (AB) to define the structure of the two logistical systems, simulating and estimating differences in e.g., required storage levels, efficiency of transport, etc. The results demonstrate that IoT supply chains have significant advantages in minimizing average product storage and shipment fluctuations by facilitating real-time and accurate information sharing among different nodes in the supply chain. IoT suppliers can estimate market demand to adjust production and transportation strategies for new orders. Consequently, heating and lighting emissions in the storage process and direct emissions in transportation per functional unit (one unit of a Li-ion cell module) are reduced by 60%–70% under middle- and low-demand scenarios and by at least 50% under high-demand scenarios. However, reducing the frequency of transportation by heavy trucks will weaken the advantages of IoT. Moreover, the overall profitability of the IoT supply chain increased by more than 30% while occupying a 10% lower market share compared to conventional supply chains under the same pricing strategy.

Dynamic nitrogen, phosphorus and potassium flow analysis of the food system in China for 2010-2019

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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China is the world's largest producer, importer, and consumer of food. However, the extensive inputs of nutrients (nitrogen (N), phosphorus (P), and potassium (K)) into the food system, coupled with careless nutrient management, have resulted in the degradation of the surrounding environment and the depletion of nutrient reserves. This study used the method of dynamic material flow analysis and provides a comprehensive quantification of N, P, and K flows and stocks through China's "production-processing-consumption" food system from 2010 to 2019. The results show that the total decade-cumulative nutrient inputs to the food system were high, while N was the highest (618.3 Tg), followed by K (280.1 Tg) and P (118.7 Tg). Chemical fertilizers accounted for 30%-60% of the total nutrient inputs (N53%, P56%, K30%). The nutrient use efficiencies (NUE) were mostly below 50% and varied greatly among different food production sectors. NUE of P for fisheries and aquaculture sector and NUE of K for livestock & poultry raising sector were both below 10%, indicating the biggest room for improvement. Nutrient losses were high. They mainly occurred through gas emissions (for N), discharge to hydrosphere and waste disposal. N gas emissions were the biggest source of N losses. The emission of NH_3 was 143.2 Tg, N_2 was 96.5 Tg, N_2O was 5.6 Tg and NO_x was 3.3 Tg. In terms of hydrosphere discharge, the total decade-cumulative discharge of N was 86.8 Tg, followed by K (73.4 Tg) and P (28.3 Tg). The total decade-cumulative discarded wastes were less than hydrosphere discharge, with N at 64.7 Tg, P at 12.8 Tg, and K at 24.8 Tg. Nutrient recycling through good practices like reapplying straw and manure to croplands achieved noticeable effects. The total decade-cumulative nutrient recycling of K (113.1 Tg) was the highest, followed by N (76.7 Tg) and P (29.5 Tg), which replaced about 15%-60% of total chemical fertilizer inputs (N 19%, P 31%, K 57%). The overall patterns of nutrient flows through the food system are high inputs, high losses and relatively low recycling, with signs of initial improvement in some sectors. The next step should be to adopt more ambitious policies for nutrient management, such as significantly reducing the use of chemical fertilizers by means of improving nutrient recycling and reducing nutrient losses. Additionally, more attention should be paid to weak spots such as increasing the NUE of P in the aquaculture sector and enhancing K recycling in the livestock & poultry raising sector.

Assessing the Social Dimension in Strategic Network Design for a Sustainable Development: The Case of Bioethanol Production in the EU

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Please note: *This abstract is based on a publication in the JIE last summer (https://doi.org/10.1111/jiec.13324), the results of which have already been presented at conferences in 2022 (LCIC, EURO, S-LCA, EcoBalance (virtually)). However, I presented the first ideas and approaches to this problem at the ISIE conference in 2019 in Beijing, and the session in which the talk was placed was attended by a comparably large audience and the talk sparked some very interesting discussion with the expert audience. This (and the fact that it was published in the JIE) is why I thought it might be interesting to present the final outcome again at the ISIE 2023. I have been in contact with Brenda from the organizing board, who acknowledged the fact and encouraged me to submit the abstract - thank you for your consideration!*

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Unlike product-specific or site-specific assessments, corporate or political sustainable decision-making on a strategic, Greenfield, and multi-regional level relies heavily on aggregated ex-ante and generic data. In contrast to environmental LCA, the complexity of social indicators, their subjective and often qualitative nature, and a lack of data render the inclusion of SLCA indicators into quantitative optimization models for strategic supply chain decision-making difficult. First, this work presents a structured process for including a comprehensive set of social aspects by selecting applicable quantitative and regionalized social indicators. Second, this approach is applied to the case of lignocellulosic, second-generation bioethanol (2G EtOH) production in the EU, which is a promising substitute for fossil and food crop-based fuels. Based on i.a. the Guidelines for Social Life Cycle Assessment of Products and Organizations (GSLCAPO), the Social Hotspots Database (SHDB), state-of-the-art literature, as well as previous work, we compile 9 maximizable social objective functions and 25 functions for social hotspot identification. They are evaluated alongside economic and 21 environmental LCA-based objective functions in a mixed-integer linear programming (MILP) model. We identify optimal strategic decisions (regional biorefinery locations and capacities in the EU, feedstock collection, EtOH transportation, and substitution of either fossil petrol or first-generation EtOH) and resulting optimal objective values for each of the social, environmental, and economic objectives. Key results show that social optimization either leads to large, labor-intensive or regionally focused, indicator-driven networks. '*Injuries and fatalities*' in the feedstock sectors of Central and Eastern European countries is the primary social hotspot. This approach allows for uncovering hidden relationships between the different objectives, for identifying Pareto-optimal trade-offs between multiple objectives, and for assessing the network's impact on the level of the overarching Sustainable Development Goals (SDGs). The approach in the study at hand is novel in its depth both in the fields of strategic network design and the European bioeconomy, and contributes to a more holistic life cycle sustainability optimization.

Understanding the relationship between resource consumption and development levels

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

William Mihkelson [1], ***Danielle Densley Tingley*** [1], ***Hadi Arbabi*** [1], ***Stephen Hincks*** [1]

1. *The University of Sheffield*

Elaborating an empirical understanding of the nexus of built-environment material stocks and consequent outcomes of human development in terms of minimum standards of living is essential to understanding opportunities and challenges for sustainable development. This is particularly important in the Global South given increased demand for resources and living standards due to rapid and unprecedented rates of urbanization coupled with deficits in living standards. Through the application of a multi-scale analysis of development outcomes and related resource provisioning in the built-environment in India, we offer novel insight into the relationship between minimum standards of living resulting from the provision of built-environment material stocks. The body of work is presented in four parts.

We firstly assess the current standard of living in relation to non-mobile built-environment material stocks aiming to provide novel insight into household deprivation of urban infrastructure and housing and evaluate the variation in perceived outcomes using complementary metrics across administrative scales.

This is followed by an empirical quantification of the relationship between minimum living standards and the provisioning of various material types used for residential buildings, highlighting tensions between the provision of carbon intensive materials and improved standards of living.

From here we quantify the accumulation of material stocked in residential buildings and roads within a case study city master-planned to accommodate urbanization and achieve high standards of living, offering insight into the quantity and composition of material stocks at the city- and sub-city scale in India for the first time and highlighting the material stock implications for providing a universal minimum standard of living to urban dwellers.

Finally, based on the existing trends within India identified previously, we quantify the resource requirements to upgrade inadequate housing and track the associated improvements to standards of living. The results highlight the significant challenge of sustainable urban development within India if current trends continue, providing insight into how effective resource efficiency measures assessed in existing studies within India may begin to decouple this relationship.

Taken together, the body of work provides an improved understanding of built-environment stock accumulation and its relationship to development outcomes in the context of rapid urbanization in the Global South. The study provides empirical evidence to support the integration of material stock assessments into urban planning and development with implications for achieving interrelated Sustainable Development Goals sub-nationally.

Construction material accounting of the Belt and Road Initiative projects

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Lingli Hou [1] ***, Tomer Fishman*** [2]***, Ranran Wang*** [1]***, Ester van der Voet*** [3]***, Asaf Tzachor*** [4]***, Heming Wang*** [5]***, Wei-Qiang Chen*** [6]***, Peng Wang*** [7]

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Construction materials constitute the largest solid material flow into cities and contribute to the most significant waste flow. Although the understanding is primarily from studies of construction material stocks (MS) and material flows (MF) at the national scale in developed countries, there is a growing interest in investigations in less-developed regions and at multiple scales. Most studies have focused on a single country or an individual city to assess their construction material use. This is because the national population, economic, and construction data are accessible and data processing for a single city has become common in recent years. Few studies have linked construction material flow accounting and economic development initiatives or investigated its spatiotemporal pattern of resource use in the Belt and Road region, where massive infrastructures are under construction.

The Belt and Road Initiative (BRI) was proposed by China in 2013 to explore new forms of international economic cooperation with new partners, facilitate regional integration, and improve resource allocation effectiveness through the largest infrastructure project in human history. China has already signed more than 200 cooperation documents with 149 countries and 32 international organizations to build the “Belt and Road”, and the number is growing as the BRI expands. However, while the BRI projects, such as high-speed railroads, oil and gas pipelines, and telecom and electricity links, connect sub-regions, they have significant resource demand.

Therefore, it is critical to further the research in the BRI region, especially the projects closely linked to BRI, accounting for construction materials. This knowledge is essential for the sustainable development of BRI projects and countries.

This study presents a novel database of construction material use in BRI projects. It estimates the main construction material use by material flow analysis (MFA) and bottom-up methods. It further explores the spatiotemporal characteristics of the material used, revealing the different types of materials utilization in the BRI countries, which provides a basis for China and the other countries to formulate environmental policies towards sustainable resource use in infrastructure and economic development. Moreover, this new database will be publicly available and continuously updated to support other researchers working on the stock-flow-services nexus of construction materials in the BRI region.

Non-optimal carbon mitigation from waste hierarchy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Xinyu HAO [1], ***Liang Dong*** [2], ***Yanran Liu*** [3], ***Xiaoling Zhang*** [2], ***Yujia Xiao*** [4], ***Kaiqin Li*** [2], ***Chengyan Yao*** [3], ***Qin Zhang*** [3], ***Guangfu Liu*** [3]

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A circular economy is an anticipated way to facilitate carbon neutrality. However, the scientific community still needs to answer whether the current circular economy's guidepost will yield optimal carbon mitigation across global regions and income groups. Focusing on the global Municipal Solid Waste(MSW) management sector, we quantify the net carbon emissions and compare the efficacies of different circular waste management strategies. It is shown that "Recycling" emits less carbon than "Energy recovery" for all regions in 2030(5.56% on average). And "Reduce" prioritizes "Recycling" for high income and upper-middle income groups. However, "Reduce" generates more carbon than "Recycling" for low income(3.01%) and lower-middle income(1.32%) groups. Our results demonstrate that "Reduce" is not the panacea for MSW management from a carbon mitigation perspective, and waste hierarchy is irregular for different contexts, which should be tailor-made. Furthermore, our study indicates that circular economy endeavors should be re-scrutinized by involving carbon flow.

Probability Distribution Analysis of Technical Parameters for Sewage Sludge Management System based on Unit process database

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 10:00: Ex-ante LCA 1 (B0.25 KOG)

Huimin Chang [1]***, Ming Xu*** [1]***, Yan Zhao*** [2]***, Anders Damgaard*** [3]***, Thomas H. Christensen*** [3]

1. *Tsinghua University,* ***2.*** *Beijing Normal University,* ***3.*** *Technical University of Denmark*

Modelling the sewage sludge management system has become a crucial aspect for evaluating and optimizing technologies. However, to make accurate assessments, it is important to generalize sewage sludge parameters as scattered data can hinder model development. Our review of 600 scientific papers found several key parameters, including technical process parameters, composition, transfer coefficients, energy and resource consumption, and pollution emission parameters. The data was standardized and found to mainly follow normal or lognormal distributions, with significant variations.

For the sewage sludge composition around the world, thickened sewage sludge contained 3.3% total solids (TS), which follow lognormal distribution. The average ash content was 32.4% of TS, with 53.3% C, 6.8% N in volatile solid (VS) and 6.7% P, 1.7% K in ash. Other parameters were the lower heating value of 22.1 MJ/kg VS and the biochemical methane potential of 0.25 m^3 CH_4/kg VS. TS content is the core parameter for water removed technology including: dewatering, deep dewatering, bio-drying and thermal drying. The average TS content was 25-30%for mechanical dewatering, 35-40%for deep dewatering, 60% for bio-drying and 90% for thermal drying. Chemical agents used in mechanical dewatering showed values of 5-15 g/kg TS. Energy consumption was low for mechanical dewatering (0.12-0.26 kWh/kg TS) and high for thermal drying (3.8 kWh/kg TS). The biological treatment of sewage sludge in terms of anaerobic digestion and composting was analysed. Biogas production varied significantly in anaerobic digestion, with a correlation between biogas production and degradation of volatile solids. Estimates of VS degradation could not be made due to the presence of organic bulking materials during composting. But The data on energy consumption and recovery was limited, and emissions into the air were scarce. The thermal treatment of sewage sludge has gained interest on incineration, gasification, and pyrolysis. Incineration is an established technology, but tradable data on air emissions is scarce. Energy recovery is close to the amount used for incinerating dried sludge (0.2 kWh/kg TS), but more energy is used for dewatered sludge (1-2 kWh/kg TS). Gasification and pyrolysis are emerging technology with four outputs: char, tar, fly ash, and syngas.

Our review of the available data on sewage sludge treatment technology found that it provides important information on the processes involved, but it is limited in regard to energy consumption and recovery as well as direct emissions. To improve consistency in mass balances, energy budgets, and emission accounts, future research should report data on inputs and outputs in a more comprehensive manner. The variability seen in biotreatment, and thermal treatment technologies requires careful control of experimental conditions to identify optimal operational settings based on desired outcomes. However, the current data is not adequate to make technical decisions. A full inventory should also take into account the management of various outputs, as this is critical to fully understand the impact of sewage sludge management technologies.

Environmental and Economic Potential of Agricultural Residues as Resources for Sustainable Waste Management

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Yooan Kim [1], ***Kyo Suh*** [1]

1. *Seoul National University*

Agricultural residues that are unavoidable in agricultural production must be properly collected and disposed of in accordance with legal standards. Agricultural residues that must be treated on a pay-as-you-go basis puts a financial burden on farmers, and an inadequate collection system leads to environmental pollution through open burning. However, agricultural residues have the potential to reduce environmental impact and increase economic returns. This study identifies the environmental, economic, and social feasibility of legalizable resource conversion methods based on the potential production of various biomass. This study estimates potential volumes and dry weights by region for 18 commodities, taking into account various factors. This study shows that most regions benefit from pelletizing agricultural residues in terms of the environment. In metropolitan cities with low residue density, however, incineration produces more environmental benefits than pelletizing. According to this study, most regions benefit from pelletizing agricultural residues in terms of the environment. In metropolitan cities with low residue density, however, incineration produces more environmental benefits than pelletizing. As the demand for agricultural residue increases, it is expected that the study's environmental, economic, and social findings will be used to develop bioenergy policies.

In-use dissipation of technology-critical elements and their potential threats to human health in the urban sphere of Vienna, Austria

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

André Baumgart [1]

1. Institute of Social Ecology (SEC), University of Natural Resouces and Life Sciences, Vienna

Novel technologies such as electric mobility and photovoltaics play a key role in mitigating climate change and transitioning towards a more sustainable society. These technologies are highly dependent on so-called technology-critical elements (TCE) and rare earths elements. The accelerating rollout of these technologies can however be expected to lead to increasing in-use dissipation to the environment, for example via corrosion and abrasion in vehicles, or weather-related effects affecting thin-film photovoltaic panels.[1] Critically, increasing concentrations of TCEs in the urban environment may lead to threats to human health due to the toxicity of some of these elements.[2]

We herein present preliminary results for the case of Vienna, Austria, triangulating a dynamic stock-flow modelling of in-use TCEs and their dissipation, with measured field data on already occurring TCE concentrations, as well as an assessment of potential health effects. We then focus on results from a bottom-up, stock-driven modelling, which combines material intensity factors for different technologies, in-use dissipation rates compiled from the literature, with reported data on fleet composition, traffic flows, as well as the installed capacity of photovoltaic panels and wind turbines within the city. Based on ranges of product lifetimes, the dissipation of TCEs Nd, La, Pr, Dy, Ce, Te and Ga are then modelled to derive insights into the status and future trajectories of TCE accumulation in the city. In addition to a business-as-usual trajectory, prospective scenarios are developed based on official policy targets as well as market dynamics, covering future mobility and renewable energy expansion plans. including a with-existing-measures and a with-additional-measures scenario reflecting official national strategies and further-reaching measures respectively.

We finalize with preliminary conclusions from our interdisciplinary synthesis of industrial ecology modelling, environmental medicine and analytical environmental chemistry, regarding the possible exceedance of toxicity concentration thresholds, mitigation measures, as well as possible health hazards of ongoing technological transitions in mobility and energy supply for the case of Vienna, Austria.

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The centennial gold cycle has widened its accumulation disparity in the Anthroposphere

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ling ZHANG [1], Qingqing Lu [1], Zengwei Yuan [2], Tao Dai [3], Wei-Qiang Chen [4], Gang Liu [5], Jun Chen [2]

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Throughout human history, gold has played a significant role, and will always be one of the critical minerals in anthroposphere. However, the extraction, processing, use, and losses along the entire gold life cycle remains hitherto not characterized, which hinders a system understanding on the spatiotemporal patterns of gold use, accumulation, and recycling potentials. This paper characterizes global gold cycle from 1900 to 2020 and particularly provides distribution pattern of total gold resources. The results show that approximately a total of 206 kt and 45 kt of gold, respectively, has been mined and recovered to meet the human demand. Within the whole life cycle of gold, the total loss in 15 years was estimated as 7483 t, most of which occurred at the production stage. Gold stock in use (mainly jewelry and gold bars/coins) has become 5-time larger and more geographically concentrated than underground reserve. Different performances of different countries at different gold life stages caused the relocation of gold resources at country level. Five countries including India, China, the USA, Russia, and Australia took up over half of the world total gold resources and will play dominate roles in future supply of gold resources. Overall, the gold redistribution has widened its accumulation disparity across country and among end-uses in the Anthroposphere; and this requires special attention facing increasing industrial demand and geopolitical tensions in the future.

Insight study of BIM-LCA Data Processing

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Building Information Modeling (BIM), the foundation of digital transformation has been used for decades in the architecture, engineering, and construction (AEC) industry. BIM is essential in building a sustainable environment considering the future climate risks. Life Cycle Assessment (LCA) is the established methodology to assess the environmental performance of buildings contributing to global climate change. In recent years, BIM-LCA integration has become critical to adopt the BIM model to calculate the environmental impacts. However, BIM-LCA integration has yet to be automat. The data processing, such as exporting BIM data to LCA tools, must be improved. Therefore, this study aims to support the automated BIM-LCA in data processing.

The objective is to identify the BIM data/ information needed for LCA and how to obtain it. More specifically, this study presents the holistic data collection from the BIM model to perform LCA of the whole building. A Norwegian Single Family Timber Building is used as a case study. The methodology includes creating the case study BIM model and data collection. Various BIM modellers employ distinct approaches to models for identical information. Therefore, the stakeholders use the building's standard data format (IFC) to exchange BM models. However, there are challenges in using the building's standard data format (IFC) to extract the information needed for LCA and require additional data/ other information to evaluate LCA. LCA needs environmental data, such as emission factors, to evaluate environmental impacts, which should be included in the BIM Model. Although this data can be input manually in BIM, the time and cost of the data entry and checking are significant. The precise quantity of materials is difficult to extract for complicated buildings and complex elements. This study classifies the available BIM data for LCA using LOD (level of development) and implements the LOD of the BIM-LCA model to get reliable data. The result shows how the modelling strategy influences the data qualities.

Exploring demand reduction and circular economy strategies for bulk materials in China

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Lulu Song** [1]**, Stijn van Ewijk** [2]**, Eric Masanet** [3]**, Takuma Watari** [4]**, Fanran Meng** [5]**, Jonathan Cullen** [5]**,
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***1.** Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, **2.** University College London, **3.** University of California, Santa Barbara, **4.** Material Cycles Division, National Institute for Environmental Studies, **5.** University of Cambridge, **6.** University of Antwerp, **7.** Institute of urban environment, CAS*

Bulk materials, including cement, concrete, metals, plastics, and glass, are integral to modern civilization, but the production of bulk materials releases large quantities of greenhouse gas emissions that are difficult to reduce because of the high temperatures and the specific process technologies required. This is particularly relevant for China, the world's largest bulk materials producer. We model the technical potential and emission savings resulting from three circular economy strategies: improved scrap recovery, more intensive use, and lifetime extension. We show that by 2060, China can source the majority of its demand for bulk materials through recycling, partly enabled by material demand falling as the population declines. Province-level results show that economic development drives up material demand initially, but also enables closed loops when material demand approaches constant saturation levels. Between now and 2060, improved scrap recovery cumulatively reduces greenhouse gas emissions from the bulk materials system by 13%. However, more intensive use, which results in reduced material demand, reduces emissions by 22%. The benefit of lifetime extension is modest, leading to only a 3% reduction in emissions. Despite the large potential for recycling, we conclude that demand reduction is equally important for meeting internationally agreed climate targets.

Circular economy and CMC: a solution to reduce the environmental footprint of ceramic matrix composites

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Florian Halter [1], ***Lars Wietschel*** [1], ***Denny Schüppel*** [1], ***Andrea Thorenz*** [2], ***Dietmar Koch*** [1], ***Axel Tuma*** [3]

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Ceramic Matrix Composites (CMC) are merged of ceramic fibers embedded in a ceramic matrix, which leads to exceptional properties such as high-temperature resistance, high strength-to-weight ratio, low thermal expansion, and high resistance to corrosive environments. On one side, these lightweight materials allow advanced applications in demanding environments that go beyond the possible use of metals and other composites. Apart from that, this material class could allow higher energy conversion efficiencies in various already existing applications and thereby contribute to the transition towards a net-zero economy. This contribution focuses on non-oxide CMCs consisting of Carbon or Silicon Carbide Fibers embedded in a Carbon or Silicon Carbide matrix (C/C, C/SiC, SiC/SiC). The technical properties enable long use-phases and new reuse options compared to alternative metal or ceramic products. CMC brakes, for example, have almost zero wear rates, allowing brake systems to endure the entire service-life of its applications, and with appropriate remanufacturing, even a second or third life gets feasible.

On the downside, the production process of CMCs is extremely energy intensive. Although no Life Cycle Assessment of CMCs has been published so far, high environmental impacts are to be expected. Both, the production of the Carbon or Silicon carbide fibers and especially the ceramic matrix build-up contributes to these impacts. There are two major options to tackle this challenge: (1) the production processes have not yet been optimized for lower energy demands and environmental impacts. (2) CMCs need to be used as efficiently as possible and material loops in the different life-cycle stages need to be closed. Besides some good specific approaches, the influence of the circularity of CMCs on their Life Cycle environmental performance has not been studied so far. Neither the environmental benefits of circulating production and fabrication residues nor the benefits of circulating End-of-Life products have been addressed in the literature yet. To address this gap, this contribution presents all physical flows and residue streams that are associated with raw material extraction, production of intermediates, fabrication into final goods, use-phase, and End-of-Life. We conduct an LCA to identify the most important environmental hotspots and compare different re-options. The goal of this study is to evaluate different CE strategies and the identification of main leverages for environmental impact reductions.

Preliminary results show that considerable amounts of residues arise during the production and fabrication processes which could be circulated. In the CMC production route *chemical vapor infiltration* (CVI), for instance, it is technically and economically feasible to circulate production aids and the process gas in closed loops, however not yet been applied in commercial processes. Regarding End-of-Life products, preliminary results based on the example of aircraft brakes show that the environmental impact of remanufactured CMC products given a second life is significantly reduced.

Spatiotemporal Features of Municipal Solid Waste Generation in China

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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The municipal solid waste (MSW) generation in China has been growing rapidly during the last few decades. Information on the MSW generation, collection and treatment is important for MSW management and for determining the potential of materials recycling and carbon emission reduction driven by the circular economy. Even though previous studies analyzed the spatiotemporal distributions and driving factors of China's MSW generation at the national or provincial level, the spatial heterogeneity and temporal evolution at the city level remain unclear. Here we build a database on MSW generation for about 300 prefecture-cities in China during 2006-2020, and have the following findings: (1) MSW generation increased from 150 Mt in 2006 to 235 Mt in 2020, and the top 10 cities with the highest waste generation (Beijing, Shanghai, Shenzhen, Chongqing, Chengdu, etc.) are mainly distributed in the Eastern and Central China; (2) MSW generation per capita increased from 1.09 kg/capita/day in 2006 to 1.20 kg/capita/day in 2020, and is approaching the level of Europe in 2020; (3) Regression modeling revealed that MSW generation is positively correlated to socioeconomic indices including urban population, population density, GDP, per capita disposable income and consumption expenditure of urban households, and urban population and GDP have the strongest positive correlation with MSW generation. By revealing the spatiotemporal features of MSW generation, we can conclude that MSW generation has great regional heterogeneity, and Chinese cities need region-specific policies for solid waste management and circular economy.

Key words: MSW generation, urban metabolism, solid waste management, China

Understanding the Key Routes of Global Dysprosium Cycle through a Trade-linked Regional Analysis

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Disna Eheliyagoda [1], ***Badrinath Veluri*** [2], ***Devarajan Ramanujan*** [3], ***Gang Liu*** [4]

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In the past three decades, rare earth elements have received significant attention as they have become indispensable for producing high-performance goods in numerous industrial sectors. Dysprosium (Dy) is one such metal in the rare earths group that is critical for contemporary clean energy technologies, automation, and electric mobility. Uncovering global Dy flows and stocks with a multiregional perspective would therefore present a holistic picture of global supply-demand chains and international trade patterns in sectors vital for industrial and societal green transition. This study aims to track nearly three decades of the anthropogenic Dy cycle (from 1988 to 2021) through a trade associated material flow analysis, in which a five regional framework is used: Mainland China, Japan, the European Union (EU), the United States of America (USA), and the Rest of the World. Results show a rising global demand trend for Dy-comprising intermediate and final products with complex trade fluctuations since 2000. China was the most prominent country with regards to Dy trade with a significant increase in trade capacity after 2017. Proposing an alternative Dy mining option to China is challenging as China was responsible for over 87% of accumulative mine production and almost 100% refinery production in past 34 years; Myanmar is emerging as an ex-China option for Dy mining from 2015. In total, 22,009 tons of intermediate products, majorly in the form of NdFeB permanent magnets accumulatively entered to the global manufacturing phase, of which almost 55% can be attributed to China. While dominating the global transport sector by employing 38% in the Dy consumption accumulatively, the electronic device, energy, household appliance, and other product sectors accounted for 4%, 11%, 23%, and 24%, respectively. The roles of upstream and downstream processes of the Dy cycle are characterized based on the regional priorities for technology improvements and meeting the domestic demand, of which regional potential in the upstream production is noticeably concentrated for China. The two largest regional Dy demands for final products in 2021 was as follows: 25% and 16% for e-bikes and wind turbines in Mainland China; 33% and 21% for conventional vehicles and industrial robots in Japan; 26% and 20% for industrial robots and wind turbines in the EU; 24% and 18% for conventional vehicles and industrial robots in the USA; 30% and 23% for conventional vehicles and magnetic resonance imaging machines in the Rest of the World. Less than 3% (i.e., 1012 tons) of globally mined Dy was recycled. However, recycling was mainly limited to NdFeB magnet scrap and swarf at the fabrication phase. The growing demand for Dy in transport and low-carbon technologies, and the non-existence of end-of-life recycling, necessitates developing circular economy strategies that can reduce the supply risk and primary material demand for Dy.

Keywords: rare earth, dysprosium, trade associated material flow analysis, end-of-life, circular strategies

The Criticality Mitigation Potential of the Circular Economy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Wiebke Hagedorn [1], ***Kathrin Greiff*** [1]

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Metals have a vital role in modern society when it comes to technological applications. This relates to major metals with a long history such as steel, but also minor metals such as NdFeB magnets. The meaning of metals becomes apparent by the steadily increasing demand for metals on global level as well as the number of elements of the periodic table, which are in-use (Hertwich et al., 2019). Further, the discussion about so-called critical raw materials represents the expected pressure resulting from the interplay between demand of certain metals and its limited supply. The related analyses are often in the field of technological development for decarbonizing economy as they require an increasing amount and diversity of metals (Schrijvers et al., 2020). The anthropogenic material cycles of metals are related to major environmental impact, first and foremost steel as it forms the largest mass flow. One ecological hotspot on global level is the material production. Here, the circular economy (CE) offers a solution to fundamentally change production systems. The promises are superiority in sustainability, resilience, and independence. It could be effective to solve multiple challenges. Most known is the concept of recycling, which fosters the use of End-of-Life material to substitute primary material (Hertwich et al., 2019). That way, already available resources are used, material extraction is avoided, and environmental impact for material provision is often reduced. Recycling systems are established, but only for major metals, which is shown by current recycling rates (Hertwich et al., 2019). In addition, recycling has its limits, and the CE offers further solution approaches to oppose the current trends.

Within a current research project two material systems are investigated regarding new ways of raw material provision based on CE principles. Firstly, a value chain of an HSS is considered, containing a high share of alloying elements. One main process is grinding, resulting in sludge. This waste stream is a mixture of steel chips, abrasive material, and lubricating oil. So far, there is no established treatment process, and most of the element get functionally lost within melting processes. Secondly, NdFeB magnets are considered. To keep the material composition and properties, the magnets are reprocessed, i.e. crushed and sintered to new products. Both processes generate raw material for powder metallurgical application without remelting. Therefore, considerable losses of metals can be avoided, which is seen as a mitigation strategy for critical raw materials.

This contribution focuses on the evaluation of the material systems from the perspective of raw material criticality and how new ways of closing ease its criticality. The questions addressed are: How critical are the included raw materials? And how can CE principles be effective mitigation strategies?

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Nature Positive Ecolabelling with Life Cycle Impact and Benefit Assessment on Environmental Footprints

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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The Evah Institute has developed Life Cycle Benefit Assessment (LCBA) methods and case studies to underpin quantitative nature-positive assessment. These are benchmarked to a range of safe operating spaces within planetary boundaries and average global per capita loadings for Product Environmental Footprint (PEF) indicators. As LCBA can define and quantify beneficial gains arising from reforestation, regeneration recycling, recovery, restoration, renewal and resilience operations it enables stakeholders to understand and minimise damages while increasingly deliver climate and biodiversity benefits.

The Global GreenTag International (GGTI) Certification Scheme has used Evah approaches to develop a NaturePositive+ Declaration (NP+D) ecolabelling program launched in 2022. The NP+D framework draws on substantial international and local work undertaken by International and National Multi-lateral Organisations and Governments and established NGOs, to put together Nature-positive offset programs that provide those parallel biodiversity and carbon co-benefits.

After shortcomings and gaps in current ecolabelling systems were identified, the NP+D solution was developed for industry uptake. NP+D certifications report climate and biodiversity outcomes of restoring, regenerating, conserving and protecting ‘Natural and Technical Nutrient Cycles’. They reach beyond current risk mitigation, ethical supply chain transparency, hazards, circular economy and life cycle assessment (LCA) schemas.
Stakeholders can use this framework, as steps on ladders to reach past net-zero carbon and extinction toward regenerative climate and biodiversity outcomes for natural, industrial and urban systems.

This work explains the new concepts and methods involved through theory, depictions and case studies. It also depicts aims to provide markets new solutions to quantify the full life cycle scope. damages and benefits. Scorings include human and environmental health; life cycle damages and benefits; ethical supply chains & modern slavery. It offers the focus and transparent methods and scoring to synergize real world transformations to nature-positive outcomes. To provide any product a single NP+D score it integrates available metrics on individual measures with transparent reporting.
Point-scores and weightings of key indicators are depicted compared on global average citizen PEF impacts within safe operating space inside planetary boundaries. The work tables these scoring systems, strengths and limitations. It is scalable from hinges to metro systems.

GGTI operates an externally verified ISO 14024 compliant 3rd Party Type 1 Ecolabel certification scheme and ISO 14025 Type III Environmental Product Declaration Program . In >172 countries, its programs are recognised by major rating tools with approvals in the United States of America, Canada, New Zealand and South Africa plus an Australian Competition and Consumer Commission Approved Certification Mark.

As LCA and LCBA involve intensive specialist work, manufacturers may progressively complete NP+D outcomes and typical scores will initially range from -100% to +100%. Measurable net-positive carbon and biodiversity outcomes may stem from reforestation, regeneration and restoration as well as from resource recycling, recovery, renewal and resilience. This framework enables stakeholders' transitioning to net- positive and regeneratively-sustainable consumption-production systems. The work will offer details, charts and chronology of N+P methods development in the context of most key global LCA and ecolabelling developments. Finally it considers LCBA theory in relation to charts of unsustainable, sustainable and net-positive development by Leiden IE Masters students supervised by two of the authors.

An Interpretable Machine Learning Model for Sustainable Biochar Production and Applications

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hannah Wang [1], ***Yuan Yao*** [2]

1. *Yale University,* ***2.*** *Center for Industrial Ecology, Yale School of the Environment, Yale University*

Biochar is a nature-based solution to combat climate change [1]; however, large-scale deployment is limited because of the uncertain sustainability effects across life cycle stages [2]. Biochar has different applications (e.g., soil amendment and water treatment) and can be produced from various biomass via thermochemical conversion pathways such as pyrolysis. Previous life cycle assessments (LCA) on biochar systems showed that variations in feedstock, conversion technologies, and end-use applications affect the life cycle impacts of biochar [3]. However, most LCA literature has focused on one or multiple specific pathways without exploring the combinations of different biomass species, conversion technologies, process configurations, and biochar applications. Conducting LCA for all possible pathways is expensive, and previous studies [4] have leveraged machine learning (ML) to accelerate the computation. Many ML models predict the technical performance of biochar for a specific application given feedstock composition and operational conditions, while few studies have estimated the sustainability performances of biochar. Most ML models are black-box, so they cannot reveal the complex interactions among applications, conversion processes, and biomass feedstock and explain how such interactions drive technical and sustainability performances. Understanding these interactions is critical for developing and optimizing large-scale biochar production and applications from both sustainability and technical perspectives [4].

The study aims to bridge the knowledge and methodological gaps by building an interpretable model to understand the complex relationships between biomass feedstock, conversion process, applications (for technical performance), and sustainability performances. As the first step, this study focuses on environmental sustainability using LCA. Our framework contained two components – physics-informed data compilation and interpretable ML model construction. Physics-informed data are compiled using the data from mechanistic process simulation and life cycle inventory database, i.e., physical constraints such as mass and energy balances are embedded in the data to inform ML training. The gradient-boosted tree-based model will be used to construct the interpretable ML model. This method enables the interpretation of parameter interactions and quantifies parameter changes' effects on the predictive LCA results.

Our model is expected to help one understand the complicated biomass-process-application interactions and how such interactions affect the technical and sustainability performances. These understandings will support decision-making for optimal biochar production and application to achieve desirable sustainable impacts given available resources and budget. Additionally, this work will present an application scenario case study for biochar applied to soil amendment, given the potential benefits of long-term carbon storage [2]. Due to the similar life cycles across biomass-based systems, we expect the framework to be easily generalized to various biochar applications and other biomass-derived products (e.g., biofuel and biomass-derived activated carbon).

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Energy-human wellbeing relationship moderated by urbanization: insights from subnational analyses in China

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Kangkang Tong [1], ***Shuyu 孙*** [1]
1. Shanghai Jiao Tong University

The relationship between energy use and human well-being, which is shaped by urbanization, is an important topic in sustainable development. Although many cross-national analyses on this topic can inform global agendas, fewer subnational explorations considering the impact of urbanization result in the lack of scientific evidence supporting local policies and actions. This research analyzed Chinese subnational data from 2000 to 2019 to reveal the dynamic relationship between energy use and objective human well-being, as well as how urbanization can influence this relationship. It is found that the log-linear correlation between the Human Development Index (HDI) and energy use and the associated greenhouse gas emissions gradually disappears from 2000 to 2019. However, HDI is found to be strongly and consistently correlated with GDP per capita and household income. The level of correlation is even stronger than that of human need satisfiers (e.g., electricity use, food, and health care). Two distinct energy-GDP pathways, i.e., high energy use-low GDP and low energy use-high GDP, are observed at the subnational level, which explains why HDI and energy use/GHGs are not correlated over time. Urbanization level has a significant moderating impact on the relationship between energy use and GDP, as well as between human need satisfiers and HDI. These findings shed light on how the energy-wellbeing relationship can differ from the national-level analysis. Furthermore, subnational policies should prioritize different human need satisfiers according to the urbanization status.

Erasmus Mundus Master's Programme in Industrial Ecology: Analysis of its Master's Theses

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ralf Aschemann [1]***, Ester van der Voet*** [2]***, Ulrika Lundqvist*** [3]

1. *University of Graz,* ***2.*** *Leiden University,* ***3.*** *Chalmers University of Technology*

From 2011 to 2017, the European Commission has funded the "Erasmus Mundus Master's Programme in Industrial Ecology" (MIND), which offers its selected students a double degree. To achieve that degree, students had to study successfully each one year (equivalent to 60 ECTS) at two of the following universities of the MIND consortium (University of Graz; Leiden University and Delft University of Technology; Chalmers University of Technology Gothenburg). MIND can be considered as the only international Industrial Ecology master programme.

During the six years period of MIND, five intakes of students were enrolled in the MIND programme, in total 78 students from 35 countries from all five continents. By January 2018, 75 of those have finished their studies successfully.

This poster will explore and analyse the master's theses of the 75 MIND alumni in order to get an overview of the research topics. By analysing the topics of these master's theses, the research questions, the geographical coverage and the methods applied are of great interest. The poster presents and discuss those in detail, considering the implications for the context of actual developments in the industrial ecology scientific community.

The derived results contribute to the future development of the emerging field of Industrial Ecology by considering the actual and early research work and perspectives of fresh alumni.

Keywords: Industrial Ecology; higher education; methods; Erasmus Mundus; analysis of master's theses

Gap-filling in greenhouse gas emissions datasets using machine learning: A how to guide.

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Luke Cullen [1], ***Andrea Marinoni*** [2], ***Jonathan Cullen*** [1]

1. University of Cambridge, 2. UiT The Arctic University of Norway

This study evaluates the ability of classification and machine learning models to fill gaps in incomplete GHG emission inventory datasets. Our results demonstrate that learning-based classification models can be effectively trained to predict facility-specific emissions given incomplete data. In scenarios with ‘simple’ gaps, simple interpolation and shallow learning models including decision trees are shown to be the most effective. As the gap-filling problem becomes more complex, simple models are insufficient and ensemble and deep learning models become the best performers, when enough input features are available. A particularly promising set of models for industrial ecology are graph representation learning algorithms due to the explicit encoding of connections between industrial plants. These connections can represent process similarities or material flow, combining attributes used in network resiliency analysis and material flow mapping.

The inclusion of any additional data, of any type, is shown to improve classification performance. The ability of the model to incrementally improve emission classification within the limited scope of the petrochemical industry, is promising for a future framework able to incrementally narrow the uncertainty distributions of GHG emissions for any industrial plant.

Beyond emission classification for individual plants, a secondary output of our learning model is a ranking of most valuable data-types obtained through principal component analysis. This ranking can be used to direct data collection to prioritise the most impactful data types, thus further accelerating improvement of facility-level GHG emissions data.

Hospital sustainability indicators and actions – a systematic literature review and framework

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Katerina Antimisaris [1], ***Lukas Messmann*** [2], ***Ricarda Fieber*** [3], ***Sandra Köhler*** [1], ***Andrea Thorenz*** [2], ***Axel Tuma*** [4]

1. University of Augsburg, Resource Lab / Centre for Climate Resilience, 2. Resource Lab / Center for Climate Resilience – Augsburg University, Germany, 3. ETH Zurich/Group for Sustainability and Technology, 4. Chair for Production & Supply Chain Management – Augsburg University, Germany

The climate crisis is increasingly linked with natural disasters, spread of infections and political conflicts, and poses a threat to both physical and mental health. Consequently, evermore people will require professional medical treatment to sustain their life quality. However, ironically, health care facilities have exert high environmental pressures and thus compromise climate, ecosystems, and human health. Among others, the healthcare sector is responsible for about 4.4 % of GHG emissions worldwide, and even 5.2 % in Germany. Hospitals thus must become more sustainable in order to pursue their principal task – to provide and sustain health. This work presents a structured literature review of (a) recommended, implemented, or planned sustainability actions (i.e., measures taken beyond legal requirements) in hospitals worldwide and (b) proposed indicators to assess a hospital's sustainability performance and the efficacy of aforementioned actions – including LCSA indicators. In detail, we aim at identifying methodological and thematical gaps in existing assessment frameworks, and at illustrating the interaction between sustainability actions and indicators answering the question: which measures need to be taken to improve specific indicator results, and which indicators can adequately measure the effects of actions taken? We develop a framework for an integrated sustainability assessment and compile a pool of indicators and actions that is structured in a four-level hierarchy: (1) sustainability dimensions, (2) categories that represent different areas and issues in a hospital setting, (3) groups of indicators and actions that pursue the same target, and (4) individual actions and indicators. This approach allows for matching indicators and actions, for identifying inconsistencies between them, as well as for deriving high-priority core indicators and actions that are deemed indispensable for measuring and improving the sustainability performance of hospitals. Key results show that, first and foremost, while a vast array of actions and indicators, e. g. to improve a hospital's waste-, energy- and water management can be identified, taxonomies and terminologies are widely heterogeneous. Second, existing assessments are widely inconsistent in their selection of indicators. Third, many of the proposed indicators are redundant with, or simplifications of LCSA indicators. Fourth, we unveil gaps and show that certain areas are methodologically or thematically under-represented in current research and practice – e.g., social responsibility, food provision, medical activities, or procurement. Lastly, we derive core indicators and actions for all sustainability dimensions. Our framework can serve as a novel guideline for indicator-based sustainability assessments and action-based improvement of hospitals' sustainability performance. The framework aims at academia and practitioners alike and could potentially be transferred to other industries. Future research should further focus on the prioritization of indicators and actions for specific hospital settings, on conducting further LCAs of products and services in a hospital setting, and on eliminating internal or political barriers for enhancing the sustainability performance.

Quantifying the circularity gap: Life Cycle Assessment (LCA) and Circularity Assessment (CA) as complementary methods for the circular redesign of complex products: A case study of industrial footwear

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Cris Garcia Saravia Ortiz de Montellano [1]***, Yvonne van der Meer*** [1]***, Ali Ghannadzadeh*** [1]

1. Aachen-Maastricht Institute for Biobased Materials (AMIBM), Faculty of Science and Engineering, Maastricht University

The sustainability and circularity assessment of multicompetent products is not straightforward. In order to provide guidance on the possibilities and limitations of the proven tools of Life Cycle Assessment (LCA) and Circularity Assessment (CA), this study uses the case of industrial footwear. Industrial Footwear has a complex global supply chain, with inputs from an extensive array of industries across the globe, such as agriculture, livestock, petrochemicals, manufacturing, logistics, and retail. Additionally, the high safety and quality standards contribute to increased product complexity and material diversity, yielding a product with more than ten components and seventy materials transported from a dozen countries.

With Europe's Circular Economy Action Plan placing special emphasis on textiles and plastics (European Commission, 2015); tackling issues of product complexity, and dematerialization has become a priority within product redesign for circularity. However, product complexity offers an extended lifetime, and material diversity allows for safety and quality. This interplay requires an understanding of the role of multi-material/multicomponent products and the impacts that this has on sustainability and CE, especially when the material mix comes from both the biological and technical cycles.

The goal of this research is to: 1) understand the influence that circular product redesign has on the environmental performance of a multicomponent product through a comparative LCA and 2) Provide guidance on the possibilities and limitations of using CA and LCA as complementary tools for decision-making. For this, two case studies were used: 1) A *business-as-usual* and 2) *circularity-designed* industrial footwear. For both cases, the system boundaries included extraction, manufacturing, transport, recycling, and disposal. For each, an LCA and CA were performed using the ISO 14040:2006 standard (International Organization for Standardization, 2006), and the Circular Transition Indicators (World Business Council for Sustainable Development, 2022), respectively.

This research provides valuable insights into the role of material selection, product complexity, global transport, value retention, and end-of-life for improved environmental and circularity performance in industrial footwear. Of particular relevance is the use of leather and polyurethane for lifetime extension versus their environmental impacts, which suggests that circular practices can significantly influence value retention at the end-of-life, but not from the LCA perspective. Most importantly, the results of this research pave the way to develop a comprehensive methodology that integrates LCA and CA for redesigning products in a circular economy.

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Assessing the Physical trade balance of metals

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Sebastien Dente [1], ***Seiji Hashimoto*** [1]
1. *Ritsumeikan University*

Metals are fundamental to our modern societies. They have become part of many objects used daily all over the world. As a result, the security of the metal supply has become vital for societies as revealed by criticality studies. In this context, tracking the flows of metals in society and assessing the stock of metals currently in use is crucial to assessing the future metal waste streams and their potential recovery. For this purpose, the use of dynamic material flow analysis and lifetime functions has become common in environmental system analysis. In the process, the management of trade data is critical as they represent a transfer of metal between countries. The standard method in the literature is to select a few products from the UN Comtrade database and use a metal content ratio to calculate the metal amount embodied in trade. In practice, however, the selection of products is seldomly justified, and the metal content of products is seldomly referenced. Besides, metals being studied separately, the information at the product level is lost.

The present work aims at tackling this issue by reviewing the practice of the material analysis of metals. For this purpose, we first selected articles in the WebOfScience core collection database based on the keyword's input "metals+material flow analysis". The 468 articles returned by the database were then reviewed and classified based on their capacity to provide metal content data and the source of these data. The sources were then added to the analysis to create a network tree of the metal content database currently used in the field of metals' material flow analysis. Finally, we complemented the database to provide a consistent metal content database in line with the UN Comtrade nomenclature. To illustrate the use of the developed metal database, we then applied it to the import and export data of the year 2020 leading to the identification of products driving the trade of metals worldwide.

Environmental Impacts of Silver Nanowires and Their Applications

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Zhengyin Piao [1]***, Amma Asantewaa Agyei Boakye*** [2]***, Yuan Yao*** [3]

1. Center for the Industrial Ecology, Yale School of the Environment, Yale University, 2. Yale University, 3. Center for Industrial Ecology, Yale School of the Environment, Yale University

Silver nanowires (AgNWs) are emerging materials with promising applications such as electronics (e.g., wearable sensor), energy storage (e.g., solar films), and medical devices (e.g., imaging). AgNWs are attractive due to their superior material properties, such as high aspect ratio at nanoscales, remarkable conductivity, and optical transparency. There is a need to thoroughly examine the environmental impacts of AgNWs, as well as their pros and cons compared to the alternatives from an environmental perspective. This can be achieved by employing life cycle assessment (LCA), which considers the value chain of AgNWs from their raw material acquisitions and manufacturing to the end-of-life. Moreover, LCAs of different AgNWs applications can inform priority areas for greener applications of nanomaterials.

Currently, LCA studies of AgNWs are limited. Available publications [1, 2] have estimated the environmental impacts of AgNWs in energy storage devices. The challenge is, however, the quality of life cycle inventory (LCI) regarding AgNWs. There are incomplete primary data of process inputs and outputs; the unclear source of secondary data for the upstream chemicals; and the lack of residue treatments. To close these research gaps, this study performs experimental analyses and process modeling to achieve a detailed and complete LCI of AgNWs. The output would not only quantify the environmental performance of AgNWs, but also provide background LCI for further AgNWs related applications.

Specifically, we focused on the polyol method, which is the most promising option for synthesizing AgNWs, considering their yield, cost, and ease of production. The mass and energy balances of AgNWs were determined by the primary data collected from the lab-scale experiments and measurements. We also applied secondary data (e.g., ecoinvent) and process modeling to quantify the LCI of the upstream production of chemical inputs for synthesizing and purifying AgNWs. For example, the LCI of silver nitrate was estimated based on the reaction of silver and nitric acid, along with the subsequent crystallization. The LCI of poly-vinylpyrrolidone is based on the amination of γ-butyrolactone, the vinylation of 2- pyrrolidone, and the polymerization of N-vinyl-2-pyrrolidone. All the process modeling followed industrial conditions and process simulations were developed in Aspen Plus, a chemical process simulation software, to estimate the mass and energy balance data that are not available. In addition, this study explores different waste treatment strategies for the residues from the synthesis and purification of AgNWs.

To determine the potential impact of AgNWs application in industry, this research will apply the developed LCI to investigate the further use of AgNWs. Specifically, this study will explore applying AgNWs as conductive layers in thin film solar cells to replace conventional materials as the first application case study. Other applications, such as soft electronics, will be further explored. The LCA results will be compared with the same application (e.g., solar cells) using counterpart materials (e.g.,indium tin oxide and conductive polymers). This comparative analysis would demonstrate whether AgNWs can be superior options for solar cells and other applications from an environmental point of view.

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The Impact of Public Lighting Systems on Mercury Emissions: A Case Study of Ireland's Street Luminaires

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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The impacts of public lighting systems on mercury emission vary depending on the production process and waste management of lighting products. In Europe, conventional outdoor lighting sources are high-pressure mercury, metal halide, high-pressure sodium, and low-pressure sodium lamps. However, since 2015, the EU market has removed high-pressure mercury lamps due to the Eco-design Directive. Each year, the lighting market sells approximately 2.6 million streetlights across Europe, and road lighting projects install 91 % of these lights, adding new lighting but mostly replacing existing ones. In 2015, there were 64 million luminaires on roadways across Europe, and 15 million were high-pressure mercury lamps. The European Union's ban on high-pressure mercury lighting systems resulted in a mass changeover to mainly high-pressure sodium lamps and LED luminaires, a new energy-efficient light source. LED technology overtook high-pressure sodium lighting systems as the total lifespan cost of LED luminaires reduced in both initial procurement costs and decreased energy consumption during use. LED technology was promoted as meeting environmental targets in lowering heavy metals, particularly mercury, emissions to the environment. Lower energy consumption of LEDs reduces demand for fossil fuel-produced electricity, and being mercury-free decreases the number of mercury-added products (MAPs) on the market. Despite these dual benefits, public lighting upgrading projects result in large quantities of waste lamps containing mercury. Ireland has recently extensively upgraded its public lighting systems from high-pressure mercury and low-pressure sodium lamps to high-pressure sodium and LED lights. This study evaluates the environmental footprint of street luminaires in Ireland with respect to mercury treatment and estimates the impact of upgrading the public lighting system with LED luminaires. This study presents a mercury material flow analysis relating to streetlighting in recent years using recycled, in-use, and stored road luminaires in Ireland. In addition, we calculated the impact of the production of LED lamps on global mercury emissions.

Risk identification of labour exploitation in medical supply chains

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Lihani Du Plessis [1]***, Jonathan Cullen*** [1]

1. *University of Cambridge*

Industrial labour exploitation impacts approximately 18.7 million people globally. This exploitation includes forced labour and children working across a range of supply chains, from cobalt mining for electric vehicles to lithium-ion batteries, and orthopaedic implants to medical supplies. Medical products such as surgical gloves and steel surgical equipment present a considerable risk for labour rights abuses due to their low manufacturing complexity. Despite organisational risk management policies, labour rights abuses are still pervasive across medical supply chains. Social sustainability research is a burgeoning field, and the number of social life cycle assessments has dramatically increased. While labour exploitation is a key dimension of social sustainability, few studies to date consider its presence in medical supply chains.

In this project we are building a framework and supply chain map to systematically assess the risk of labour exploitation in England's National Health System (NHS) medical supply chains. The framework will help medical procurement teams identify medical supplies that have a high risk for labour exploitation and require further screening and potential remedial action. This poster presents an initial identification of the common hotspots and characteristics of risk (such as product type, material complexity, country of origin etc.) associated with labour exploitation. We will use the common patterns, along with data from the NHS, grey, and published literature to create a risk assessment framework. The framework will be applied to the supply chain map of medical products purchased by the NHS (created using methods such as material flow analysis, input-output, or Bayesian neural networks) to identify the scale and location of risk for labour exploitation. We expect the study to identify the highest product risk categories for labour exploitation and highlight areas where the NHS should focus investigations and regulatory interventions such as more detailed supply chain mapping (beyond Tier 1), supplier collaboration to improve working conditions, and improved organisational policies.

This is a student abstract.

Nexus of process integration and life-cycle assessment for industrial decarbonization

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jiaqi Lu [1], *Dungang Gu* [1], *Yuhang Lou* [1], *Guanghui Li* [1], *Pinhua Rao* [1], *Nan Zhang* [2]

1. Shanghai University of Engineering Science, 2. The University of Manchester

The achievement of carbon neutrality needs a systematic transition in the production pattern since the Industrial Revolution. Compared with fossil fuel combustion for energy supply, the decarbonization of industrial processes is more intractable because the expansion of renewable energy cannot directly avoid the greenhouse gas (GHG) from chemical reactions. Besides the experimental development of advanced technologies, the nexus of process integration and life-cycle assessment (LCA) can support the maximization of GHG emission reduction for the current and future industrial processes. The origin of process integration is applied for energy saving and cost reduction in the chemical industry, such as the well-known pinch analysis. The essence of process integration is to use mathematical language for expressing the quantitative relationship among the material input, energy balance, product yield, pollutant emissions, etc. of a process. Those input and output process data are commonly a fixed or averaged value in the life-cycle inventory analysis, which can be simulated by a process model with various design and operating variables. Thus, the nexus of process integration and LCA can bring a technical dimension to the evaluated environmental impacts. The first function of this method can quantify the influence of design parameters (e.g., equipment size and material) and operating conditions (e.g., throughput and reaction temperature) on the process inventory data, ultimately, on the life-cycle environmental impacts. Based on the complex chemical thermodynamics and kinetics, the obtained quantitative relationship is usually a non-linear model. Chances are that an optimal process design exists with minimal life-cycle environmental impacts, which can be derived by non-linear programming. With a case study on membrane desalination technologies, this idea has been realized in our recent practice. We quantified the life-cycle GHG emissions (carbon footprint) associated with the production, operation, and waste management of the membrane module. A finite element method was applied to model the electricity consumption for desalination under various module designs and operating conditions. The carbon footprint per produced water was minimized under various scenarios to discuss the optimal process design toward carbon neutrality. Another application of the nexus method is to facilitate the ex-ante assessment of emerging technologies. Because the inventory data for LCA is commonly based on the industrial production system, the conventional practice is an ex-post evaluation after the industrial application of technologies. To reveal the potential environmental hotspots or benefits of emerging technologies, the process integration can support the scaling up of uncertain lab-scale experiments into an industrial scale. Mature chemical reaction models, process simulation software, and data-driven methods (e.g., machine learning) will be alternatives appl predicting the industrial-scale inventory data for LCA. Finally, the process design of emerging technologies can be modified at the lab scale to reduce the potential environmental footprint during the industrial application. To sum up, the nexus of process integration and LCA can not only generate technical suggestions for the decarbonization of mature industrial processes, but also reveal potential life-cycle environmental impacts of emerging technologies for the green design before industrial application.

How does China's emerging middle-income group reshape consumption patterns and carbon footprint?

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:28: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Xinzhu Zheng [1]

1. China University of Petroleum - Beijing

The lifestyle changes of China's emerging middle-income group have raised severe concerns about growing carbon emissions while stimulating consumption. Converting the qualitative concerns to quantitative understanding and guiding the group to low-carbon lifestyles rather than copying the carbon-intensive ones of the rich is critical for achieving the goal of common prosperity and carbon neutrality simultaneously. This study performs the quantitative assessment by combining machine learning, input-output model, and household survey data and compares the carbon emission impacts of various income-increasing paths and their policy mix. The results show that if the scale of the middle-income group doubles during 2018-2030 (i.e., a 24% increase in the share of the national population with an annual income of RMB 33,000-80,000 at constant 2018 prices), the consumption upgrade of the emerging middle-income groups would bring an additional carbon emission of 0.48-0.60 billion tons in 2030. Compared to the business-as-usual scenario, the mitigation rate needs to increase by 9.5-11.9% to offset the emission increase. Second, in the case that only the impacts of income increase are considered, the emerging middle-income group's carbon emissions are significantly lower than those of the original middle-income group (0.2-0.4t difference at the per-capita level). The gaps can be explained by the contributions of other factors (e.g., socioeconomic characteristics, consumer psychology, behavioral habits, etc.) and imply the mitigation potentials in climbing the income ladder. Third, urbanization brings more marginal carbon emission impacts than human capital enhancement and social security system improvement. The mix of these policies shows synergetic or counter-productive effects depending on the policy implementation context.

The conceptualisation of circular road construction: A case study in Norway

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Alexander Grødum Vetnes [1], ***Reyn O'Born*** [1]

1. *University of Agder*

Introduction: Circular infrastructure necessitates holistic planning, design, and implementation combined with a systems thinking approach. The main challenges in large road infrastructure projects is to determine how circular economy concepts can be implemented and how they can be appropriately measured. While there does exist several examples of circular economy design and metrics for buildings, there is very little literature that explicitly attempts to conceptsualise circular economy measures in road construction. This study is an exploration of the concept of a circular road, which will be applied on a real life case study for the E39 Betna-Hesnes highway project in Norway. The main objective of this study is to make a first attempt at defining what a circular road entails and to discover how road construction can best implement these concepts.

Methods: A mixed method approach is used where literature on circular economy of infrastructure is used to develop a basic framework for what a circular road might entail. This will be followed by carrying out surveys and semi-structured interviews of road construction industry actors to help define this framework more clearly and to understand how to best implement circular road construction principles. A case study will also be carried out on an existing road construction project to determine if or how circular economy could best be implemented, primarily through re-use of materials, low-emission construction methods, incentive frameworks, and planning for circularity throughout the lifetime of the road.

Results and discussion: The main results of this study will be to help define the emergent concept of circular road construction. The literature on the concept of a circular road is virtually non-existent despite the overall importance and outsized environmental impacts of road infrastructure projects. The results of this study should be used to further the development of circular concepts in road construction and will also contribute directly to two new research projects in Norway relating to circular road construction. The secondary impact is on how to best implement new concepts of circularity and to begin the discussion on how circularity should be measured in road construction.

Assessing the Influence of Information Feedback on Energy-Efficient Behaviors of Households with Agent-Based Model – A Case Study in the Usage of Residential Air Conditioners

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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Since the last century, the rapid growth of global industry and economy has caused a surge in population and made urbanization an irreversible trend, as well as the steady increase in building energy usage and building-related greenhouse gas emissions. According to statistics, buildings have been one of the sectors with the highest energy intensity nowadays, contributing about 30-40% of total world energy consumption annually, among which the demand for residential buildings accounts for the most significant part. Numerous studies have indicated that occupant behavior is the critical factor affecting the energy performance of buildings. Furthermore, compared with the substantial capital and time cost required for renovating physical facilities, improving the daily consumption habits of occupants may be a more economical and effective method estimated to bring considerable energy-saving benefits (about 4-30%).

In Taiwan, more than 80% of residential energy use is in the form of electricity, a kind of invisible resource difficult for people to perceive when using it and hence often lead to overconsumption. To address this problem, experts put forward the concept of “feedback”, expecting to utilize increasingly prevalent information and communication technologies (ICTs), such as commonly seen automated measuring tools like smart meters, in combination with in-home displays (IHD), mobile devices, and computers as media to provide users with real-time or continuous consumption information. This approach is considered able to enhance users’ awareness of their own electricity usage and thereby change behavior routines for the purpose of conserving energy. However, previous research mainly focuses on observing the discrepancy in electricity consumption before and after small-scale field experiments, conducting qualitative interviews with the participants, or evaluating the technological penetration of smart metering platforms under different policy scenarios by simulation approaches. In contrast, there are still few direct descriptions of how feedback affects consumer behaviors, and the intention-behavior gap of individuals is often ignored in studies. Additionally, several confounding factors can also cause variation in results, including the duration and scale of trials, sampling methodologies, socio-demographic characteristics of target groups, etc. Therefore, still no effective methods for quantifying the energy-saving potential of feedback technologies have been proposed.

To further evaluate the utility of feedback techniques, an Agent-Based Model was developed as part of this research to simulate occupant usage patterns of residential air conditioners in Daan District, Taipei City, using the GAMA platform. Ambient temperature was applied as the trigger for residents to operate the appliances; educational level and size of each household, as well as each member’s age, daily schedule, and occupancy pattern of the dwelling were given as input for this model based on the actual demographic data of this region. Through bottom-up simulation, we obtained the residential air conditioning load profile as well as the associated electricity costs. Then, various feedback strategies, such as time-of-use rates and social norm comparison (peer comparison), were introduced to investigate the difference in final electricity consumption caused by user behavior changes. This study established a preliminary assessment model based on the influence of information feedback on individual behavior, which not only quantified the potential energy efficiency benefits of relevant technologies but also emphasized the relationship between feedback content, energy-saving incentives, and behavior. The existing framework of this model can be extended to include other residential energy end-use categories, and analyze the effectiveness of feedback on household conservation more comprehensively.

Recycling potential of Aluminium used in passenger vehicles in Latin America

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Estefania Orquera [1], ***Zhengyang Zhang*** [1], ***Guochang Xu*** [2], ***Xianlai Zeng*** [2], ***Kazuyo Matsubae*** [1]

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Latin America and the Caribbean region (LAC) have called attention due to its important deposits of primary resources required in many industrial activities. The LAC shows an expansion in private car ownership, from 2005 to 2015 the new vehicle registration has grown almost by 80%[1]. Such trends represent a rapid growth in the demand for materials such as Aluminum (Al). Considering the potential recyclable amount of Al from vehicles when they rich the end of their service life (ELVs), the automotive sector in LAC could play an important role in transitioning from a material consumer to provider [2,3].

This study aims to model the flow of Al sourced from passenger vehicles in the LAC and to propose circularity strategies for its recovery and efficient management of secondary Al from country to a regional level.

Methods

The number of ELVs from 2008 to 2050 was estimated by applying the Population Balance Model based on the ELVs lifespans distribution and the use of the population and GDP growth as vehicles' growing rate factors.[4] The flow and stock of passenger vehicle-derived Al in Mexico, Brazil, Argentina and Ecuador were assessed by the material flow analysis (MFA) for the period 2008-2050. The targeted vehicles are categorized into combustion vehicles, electric vehicles and hybrid electric vehicles. Data on the vehicle sector was obtained from the automotive associations of the four countries from 1990 to 2021.[5]

Results

Brazil's ELVs will reach its highest point in 2030 with 2,437 million units, and the trends are almost stabilized increasing in a 6% in 2050 with 2,581 million units. The number of ELVs in Argentina will rise to 0.56 million in 2031, and then decline to 0.54 million in 2050. Mexico and Ecuador show a similar increasing trend during the assess period. Mexico presents an apparent stabilization from 2030 and 2040 with an average of 1,263 million of ELVs continuing to rise to 1,770 million in 2050. While the number of ELVs in Ecuador will reach 0.17 million units in 2050. The rest of the results will be presented in the conference.

Conclusion

It is clear that a large number of ELVs will be available in the targeted countries in the coming years. Knowing the flows of Al derived from these ELVs helps to establish strategies to utilize secondary Al resources and provide circularity options for the context of Latin America.

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Material Stock-Flow-Service and Circularity Potential of Buildings in Singapore

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Anthony Meijer* [1], *Mohit Arora* [2], *Lynette Cheah* [1]**

***1.** Singapore University of Technology and Design, **2.** BBC*

The buildings and construction sector plays a vital role in socio-economic development, while being a primary consumer of resources. In Singapore, this sector is highly reliant on imports, and the city-state is expected to double its building stock by year 2050. Estimates of city-scale building material stock and flows can help planners appreciate the scale of material demand, contributing towards the potential to pursue material circularity and decarbonisation. In this study, we apply a bottom-up, retrospective material flow analysis (MFA) to track the stock, flows and embodied carbon, of concrete and steel for all buildings in Singapore, from years 2010 to 2020. The goal is to estimate total building stock across all building typologies, and total material stocks of concrete and steel, along with annual in- and outflows. We further estimate future outflows of concrete and steel based on building demolition trends, to unveil opportunities for secondary resource utilization and minimize import dependence for construction materials. Finally, we explore the scale of services that the building stock provides for housing, offices, and accommodation of industrial activities, and whether this has improved over last decade in terms of material intensity.

We are able to show that most material inflows fulfil residential sector demand, while the largest outflow originated from the demolition of private industrial buildings. Within the 10-year period of 2010-2020, the concrete and steel stock has been growing 3% per annum on average, increasing by 61.8 Mt, reaching 257.5 Mt in 2020. This increase required 6.1 Mt of annual material inflows while annual material outflows averaged 1.8 Mt. The cumulative outflows for the next 10 years can meet around 37% of total material demanded over the last 10 years. As of 2020, embodied carbon in public residential buildings is the highest (93.0 MtCO2e) among all building types, followed by private residential buildings at 64.7 MtCO2e and private industrial buildings at 45.4 MtCO2e. Material intensity, in terms of metric tonnes per floor area, has remained stable. There is an immediate opportunity to step up secondary resource use, through policies encouraging material circularity, thereby reducing the reliance on material imports. Focusing on secondary resource utilization and reuse can contribute to low-carbon and circular built environment.

The evolution of electronic waste in Canada

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Komal Habib [1]

***1.** University of Waterloo*

The digitization of day-to-day operations in every sector of modern life has led to a rapid growth in the consumption of electrical and electronic equipment (EEE), consequently giving rise to their waste counterpart, waste electrical and electronic equipment (WEEE) that is known generally as electronic waste (e-waste). Detailed analysis of e-waste generation and composition is of utmost importance for proper management of growing e-waste stream worldwide. Considering the absence of such comprehensive and up-to-date studies in Canada, this work presents the first estimate of put-on-market EEE, the in-use stocks of EEE and e-waste generation in Canada from 1971 to 2030 for 51 product categories comprising 198 product types. Using a dynamic material flow analysis (MFA), the put-on-market EEE is estimated based on trade data retrieved from national and international import and export statistics, and the in-use stocks of EEE and the resulting e-waste are calculated using the Weibull distribution function. The results show that the total mass of EEE within the 60-year period is estimated to be 42.3 million tonnes, with an annual average growth rate of approximately 0.5%. By 2030, the total accumulated in-use stock of EEE is estimated to exceed 309 million tonnes. The estimated e-waste over the 60-year timespan is 29.1 million tonnes. The total annual e-waste generation in Canada is calculated to be 252 kilo tonnes (kt) and 954 kt in the years 2000 and 2020 respectively, which is estimated to reach 1.2 million tonnes by 2030. The e-waste generation per capita increased from 8.3 kg in 2000 to 25.3 kg in 2020 and is estimated to reach 31.5 kg by 2030. This quantification provides valuable insights to policymakers for setting up targets for waste reduction and to identify the resource circularity potential for efficient management of e-waste.

How industrial ecology scholars may shape narratives to advance sustainability transitions

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Sina Leipold [1]

1. Helmholtz Centre for Environmental Research

Advancement in sustainability transitions requires shaping effective narratives that engage and inspire stakeholders. Environmental governance offers a wealth of insights into the forms and content of narratives, their adoption and impact. However, there is a gap in understanding how to effectively shape narratives to drive sustainability transitions.

Our framework integrates insights into the form and content of narratives, the messengers, and presentation conditions to advance our understanding of how individuals and collectives can shape narratives.

This research uses relevant examples and offers valuable implications for industrial ecology communities to better communicate and implement novel solutions for addressing global environmental change, by exploring the benefits and risks of shaping narratives for transitions.

The sharing economy is not always greener: A Review and consolidation of empirical evidence

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tamar Meshulam [1], ***Sarah Goldberg*** [1], ***Diana Ivanova*** [2], ***Tamar Makov*** [1]

1. *Ben Gurion University of the Negev*, **2.** *University of Leeds*

Although the digital sharing economy is commonly thought to deliver environmental benefits through more efficient use of existing product stocks, whether this is the case is not yet well understood. Reviewing papers that directly assess the environmental impacts of digital sharing and consolidating the results of empirically-driven analyses, we find that digital sharing does not necessarily reduce environmental impacts. We examine if and how different factors relating to sharing platform and research design could affect the reported environmental outcomes. Our results show that sharing of goods is generally associated with better environmental outcomes compared to sharing of accommodation or mobility, with ride-hailing emerging as particularly prone to negative environmental outcomes. We find that resource ownership structure (centralized vs. peer-to-peer) and whether sharing is free or for-pay generally do not explain the variation in environmental performance in the reviewed studies. We argue that more attention should be given to some of the underlying causes for the mixed environmental impact including platform logistics and consumer choice. We conclude by highlighting remaining research gaps and offer guidance on how the sharing economy could be steered to more environmental paths.

Opportunities to achieve carbon neutrality in buildings in China

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Lulu Song [1]

***1.** Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences*

Building, along with food and clothing, is one of the most pressing basic human needs. Chinese buildings are becoming a large source of global emissions. The GHG emissions for the life cycle of buildings account for ~50% of the total GHG emissions in China. With the deepening of urbanization, energy use in buildings is expected to grow. Unless measures are urgently taken to change the way buildings are constructed or operated, it is expected that soaring needs for buildings will drive up demand for materials and energy, placing ambitious climate targets at risk. To explore how this growth can be slowed, we model the technical potential and emission savings of nine scenarios for Chinese buildings, covering the entire life cycle from building materials production, building construction, and building operation to end-of-life management. We show that circular economy approaches in building material production, combined with cost-effective efficient energy improvement in the life cycle of buildings can achieve negative emissions in buildings by 2060. The circular economy strategies could reduce material consumption by 80% and reach 60% emissions reductions before 2060 while turning the material production and building construction into a net carbon sink combined with an additional energy efficiency improvement. Implementing several energy efficiency strategies together can reduce emissions by 80% in building operation. Province-level results show that economic development drives up emissions but enables a closed loop when material demand ultimately reaches saturation. Our work improves the representation of the circular economy in energy and emission savings and provides insight into long-term dynamics in building carbon neutrality.

A Systematic Review of the Home Appliances Industry Sustainability Reports

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Utkuhan Genc* [1], *Kendrick Hardaway* [1], *John Mulrow* [1]**

1. *Purdue University*

Energy consumption by home appliances accounts for a significant portion of the carbon emissions from households. Globally, carbon emissions from appliances in 2021 were approximately 2,859 Mt, roughly equivalent to 13.6% of the overall emissions from energy combustion and industrial processes (IEA, 2022a, IEA 2022b). Consequently, the pressure from environmentally conscious customers is forcing appliance and technology retailers (i.e., appliances online, Curry's) to demand companies evaluate their production and use phase impacts on the environment. Effectively, it is a requirement to make appliance efficiency a priority rather than a novelty feature (O. Unluer, personal communication, July 31, 2022). However, how these requirements are measured across the industry has been unclear and misleading as Siew (2015)'s comprehensive review of the sustainability reports tools highlighted.

Siew (2015) found that lack of standardization, the use of reports to hide actual practices, and the use of "greenwashing" to manipulate stakeholders are three main problems for the industry's sustainability reports. However, even if these three issues are addressed, from a technical perspective two major problems exist. First, the sustainability reports do not account for climate uncertainties and thus lack robustness and second, feedback effects are ignored which can overinflate the actual carbon reductions from efficiency improvements on the home appliances. To date, no reviews of sustainability reports have analyzed this shortcoming in-home appliance sustainability reports.

In this study, we will look at home appliance companies' latest sustainability reports to perform a systematic literature review. The reports will be reviewed in five categories: inclusion of efficiency improvements (water and energy), carbon emission reductions, net zero commitments, recognition of uncertainties (and risk associated with it), and discussion on feedback effects. In addition, the differences between the measures used in these five categories will be reviewed to understand the standardization issues in sustainability reports in the home appliances industry. The review will look at all 150+ home appliance manufacturers, and systematically review the ones that have a sustainability report. Out of these 150+ brands, some of them are owned by larger conglomerates thus a review will only focus on the parent company report.

Our preliminary review of four of the largest 10 companies showed that feedback effects are mentioned only once while uncertainty or risk-related outcomes were not found in any of the four reports we did a thorough analysis on. The implications are that the industry overestimates the ability to reduce carbon emissions. Therefore, our analysis could point toward new ways for the industry and regulatory bodies to bring down home appliance environmental impacts.

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Development of a "Co-learning" basis construction method for the realization of a "Beyond Zero-Carbon" society

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hideaki KURISHIMA [1], ***Rumi Yatagawa*** [1], ***Satoru Yamashiro*** [1], ***Jun Inokuma*** [1], ***Hidefumi Kurasaka*** [2], ***Fumihiko Miyazaki*** [2], ***Yasunori Kikuchi*** [3]

1. *Shibaura Institute of Technology,* ***2.*** *Chiba University,* ***3.*** *The University of Tokyo*

Climate change is projected to have serious and enormous impacts on ecosystems and human security. At the same time, local communities are facing challenges such as super-aging, declining populations, and stagnation of key industries. A transition to a "Beyond Zero-Carbon" society that "simultaneously solves" climate change and regional issues is required. To achieve this, it is necessary for citizens, experts, and business entities to work together to change mindsets (paradigm shift) and develop innovative technologies and social frameworks while building a relationship of trust.

Local people are the experts of the region who know the local prosperities (assets) which should be transferred to the next generation such as local industry and culture. They are also the beneficiary of the region's prosperous future. And researchers from research institutes can provide scientific insights such as climate change, and advice on the technologies and options which contribute to the local prosperities. Companies have practical perspectives for business operations such as market demand forecasting and profitability. It is important for the realization of a "Beyond Zero-Carbon" society that local people, researchers, and companies share a common vision for the future of the region and complement and cooperate with each other based on a good understanding of each other's characteristics. We call these efforts "Co-learning."

To build a relationship of trust between local people, researchers, and companies, our project is committed to developing a methodology to build a basis for "Co-learning" in a region. In this project, we consider a "Co-learning" basis in a region is composed of three pillars; "Koto (Event)" creation, "Ba (Place)" creation, and "Hito (Human)" development. In "Koto" creation, we are developing "Co-learning" method including "how and what" of the regional issues to be discussed and sharing various issues, knowledge, and skills in the community. Researchers in the fields of public philosophy, sociology, and science communication are involved in discussions on "Koto" creation. In "Ba" creation, we are working with architects to consider the requirements for a "Co-learning" space where people naturally gather and deliberate. Moreover, construction of a virtual "Co-learning" space using the Internet is being considered. In terms of "Hito" development, we aim to develop local people who have a certain degree of specialized knowledge and can think through backcasting, as well as researchers who respect the region. Cooperation between educators and science communicators is essential for its realization.

A "Co-learning" basis is an important key for local communities to realize the transition to a "Beyond Zero-Carbon" society. In this presentation, we will introduce the specific efforts and methodology of our project to build a "Co-learning" basis. We would also like to discuss the importance of "Co-learning" in the social implementation of technologies and systems that will lead to the realization of a "Beyond Zero-Carbon" society.

The Adoption of Failure Mode and Effects Analysis (FMEA) to Assess Environmental Risks in Construction

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Wahbi Albasyouni [1], ***Oliver Heidrich*** [2], ***John Kamara*** [3]

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The construction industry has significant environmental impacts due to for example, raw materials extraction and associated deforestation, air pollution, resources consumption, noise pollution, and high generation of waste (Oke et al. 2019). Even though many of these impacts cannot be eliminated completely, yet, with the right approach they can be reduced (Ijigah et al. 2013). To identify what and how, environmental risk assessment is essential. Failure Mode and Effects Analysis (FMEA) is a proactive systematic approach to evaluate the process to identify and reduce possible failures and emission hotspots (Vazdani et al. 2017). It can be used as an environmental risk assessment tool to analyse the environmental effects caused by errors, deficiencies, and technical issues (Ralcheva 2019). FMEA is mainly used as a quality management tool, but recent studies suggested the significance of using FMEA as a decision tool for companies that want to take environmental and ecological issues seriously (Ahsen et al. 2022). This presentation reports on the adoption of FMEA and how it can help to assess environmental risks in the construction sector in developing countries. The motive behind implementing FMEA is not only to decrease operational failures, but to provide a checklist of the environmental impacts and how these can be controlled (Ralcheva 2019). Many studies discussed the potential of FMEA in the field of environmental risk assessment, but only few proposed the practical implementation of this approach (Roszak et al. 2015). Current statistics of the environmental impact of the construction sector in developing countries raises the concerns and urgent need for a systematic assessment, such as FMEA. Hence, a conceptual model is presented that demonstrated the framework and practical implementation of FMEA to identify and assess environmental risks. We share our experiences and data, but we also want to learn and obtain some feedback from the industrial ecology members community.

Evaluation of Climate-change Adaptation Measures from the Perspective of Co-benefits with Mitigation - Case Study of Logging Trees in River Channels -

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:21: Mitigation Policies (short presentations) (A1.44 KOG)

Sotaro Takenaka [1], ***Kiyo Kurisu*** [1], ***Kensuke Fukushi*** [1]

1. The University of Tokyo

Since there are climate change risks that cannot be prevented by mitigation measures alone, adaptation measures to climate change have become increasingly important. While there is a social demand for adaptation measures that bring co-benefits with mitigation, there are few studies that quantitatively evaluate changes in greenhouse gas (GHG) emissions derived from adaptation measures.

In order to provide an outline of multi-perspective evaluation for adaptation measures including GHG reduction, we picked up the case of cutting down trees in a river channel for flood control. When the logged trees are used as biomass, they could contribute to both mitigation and adaptation.

In Yamagata Prefecture, located in the Tohoku region of Japan, there is a river called the Mogami River with a basin area of 7,040 km2, which has experienced four floods in the last 20 years. Currently, the trees in the Mogami River channel are cut down for flood control and chipped to be used as sources of power and heat. Unlike cutting trees in forests, there are various restrictions on cutting trees in river channels. For example, shrubs interfere with logging, so trees are cut in the winter when the snow flattens the shrubs. There is also the restriction that trees on private property and trees nesting birds cannot be cut. In addition, the size of the tree should be carefully evaluated before cutting, as the size of the diameter determines the profit.

We conducted a Life Cycle Assessment (LCA) to evaluate the mitigation effects of the tree utilizations, such as power and heat. In the target area, cut-down trees are naturally dried and chipped. The logs are used for boilers at three facilities, where the heat generated is used for heating and boiling, replacing heavy oil and light oil. In addition, a part of branches and leaves are used for power generation. The foreground data were collected through field surveys and interviews with business operators. One-ton wet weight of cut-down tree was set as a functional unit. GHG emissions were calculated and the decarbonization benefits of fossil fuel substitution were analyzed. Changes in carbon stocks, absorption by trees, and GHG emissions from construction were not considered. The results showed that the overall GHG emission was -430 kg-CO2eq./t-wet log. The significant reduction in GHG emission was derived by the natural-drying process, shorter transportation due to local biomass use, and no land use change. The monetary value of this GHG-reduction effect was estimated using the carbon price and the purchase price of renewable energy.

We also calculated the annual flood damage before and after the logging and estimated the amount of expected flood-damage reduction. Then, we evaluated the monetary value of adaptation measure alone and the monetary value of the mitigation effect by using logged trees.

LCA Applications in the Developing World – Current Status, Challenges & Opportunities

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Amma Asantewaa Agyei Boakye [1], ***Yuan Yao*** [1]

1. *Yale University*

Life-cycle assessment (LCA) applications offer many environmental, social, and economic benefits, informing designers and policymakers to make sustainable decisions throughout product, process, and system lifespans. Unsurprisingly, diverse stakeholders have increasingly adopted LCAs in the developed world over the years[1], and the focus of recent research in some developing countries has progressed from conventional ex-post LCA approaches to forward-looking LCAs. With the developing world (the Global South) anticipated to industrialize rapidly in the coming years to achieve UN 2030 Sustainable Development Goals (SDGs) [2], LCA will play a critical role in ensuring that these emerging economies build sustainable systems from the start. Despite the usefulness of LCA and the progression in its application in the developed world, past studies suggest [3] that the developing world is lagging in applying conventional LCA practices to sustainable design and policy development.

Some past studies [4,5] have explored LCA application in specific countries; however, a comprehensive comparative assessment of LCA research and application globally based on region-specific economic development is yet to be conducted. To accomplish this, there is a need for a thorough evaluation of LCA literature to identify trends in LCA application across various sectors and geographic locations in the past. One hypothesis for the low LCA application in the developing world is the under-representation of LCI databases from developing countries. To test this hypothesis, there is a need to evaluate widely used LCI databases for regional and sectoral representation to inform future database improvements. Together, these activities will provide a thorough overview of the current state of LCA application in the developing world and identify possible causes of under-application in some geographies to inform focused improvements. The findings from this literature analysis may inform pathways to broader the application and improve the utility of LCA in the developing world.

In line with the objectives discussed above, this talk will (1) present the results of assessing LCA literature published for technologies in the developed world in the last three years, (2) discuss the geographical and sectoral representation of datasets, and (3) provide recommendations on how to accelerate LCA use to support sustainable design in emerging economies based on lessons learned from the developed world. The results of this study will help inform the direction of future work for the LCA research community, database developers, industry stakeholders, and policymakers. More specifically, this work will provide strategic insights into how these stakeholders can accelerate the use of LCAs to support sustainable development in a rapidly industrializing developing world.

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The Wastepaper Collection System in Hong Kong: Perspectives from Stakeholders, Value Chain and Policy-price-behaviour

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

PEIXIU CHEN [1]***, Benjamin Steuer*** [1]

1. *The Hong Kong University of Science and Technology*

Million tons of municipal solid waste was generated in Hong Kong, but only one-third of it was collected for recycling, with the rest being sent to landfill. Wastepaper, which is the second largest recyclable fraction, recycling rates decreased dramatically in recent ten years. To alleviate the increasingly saturated landfills and reduce environmental consequences, developing an effective wastepaper recovery management system is indispensable for Hong Kong's waste management. Collection, as the first stage of the recycling process, constitutes a key element for overall recycling rates. Therefore, it is essential to understand how the current wastepaper recovery management collection system works from social and economic perspectives, which offers support to policymakers in the field of improving the effectiveness of wastepaper management in Hong Kong.

This study aims to explore the stakeholders' social network interaction, value chain, and policy-price-behavior dynamics in the wastepaper collection system in Hong Kong through both quantitative and qualitative analysis. These findings are used to formulate suggestions for effective policies for the wastepaper collection system in waste management.

Both quantitative and qualitative interviews of the attitudes, expectations and behavior patterns of wastepaper collection stakeholders were conducted in Hong Kong. Over 40 in-depth interviews were conducted with stakeholders involved in the post-consumer wastepaper collection system and more than 470 instances of recyclable waste transactions were documented to capture the value chain and the price dynamic in the wastepaper collection system. Policy-price-behavior analysis was used to identify existing key institutional barriers to the wastepaper collection system.

The results show that the majority of stakeholders in Hong Kong's wastepaper collection are frontline collectors, pre-processors, and exporters. Cleaners, informal waste collectors, and retired residents are the majority frontline collectors, and they contribute to collecting 447.4kg, 488.0kg, and 200.2 kg of wastepaper per month on average. Pre-processors collected 107.6 tons of wastepaper per month from frontline collectors on average and around 25.9 thousand HKD (3,320.5 USD) net profit was made from wastepaper collection and transactions to exporters. The accumulative added value of the wastepaper was estimated to be around 1800 HKD/t (230.7 USD/t) along this stakeholders' value chain. However, the wastepaper collection system is highly fragile as price volatilities undermine systemic investment strategies and recycling business developments. Wastepaper international trading policies have a substantial impact on prices and by implication on upstream stakeholders' transaction behavior patterns. Various policy measures are needed to address these challenges to build up an effective wastepaper collection system. Overall, the study provides a novel and comprehensive understanding of the wastepaper collection in the city and thereby helps in making effective policies in support of local waste recycling management.

Keywords: Wastepaper recycling; Stakeholder network; Value chain; Hong Kong;

Australian Aboriginal knowledge and alternative designs for the circular economy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Laura Vecoli [1]

1. Leiden University, CML

This research explores Australian Aboriginal knowledge, to inform ontologically-oriented and inclusive designs for a circular economy (CE). Human activity has cumulatively reached the magnitude of geological force, causing changes to ecosystems, leading to not only climate change, but also biodiversity loss, ocean acidification, changes in land use and hydrological cycles, to name only a few. The urgency of these environmental pressures is increasingly evident, and the CE is gaining momentum as a model to achieve growth decoupled from environmental degradation. However, CE designs and articulations largely stem from few – and largely Western, academic – knowledge producers.

Complex systems theory shows that systems are the sources of their own problems. It is therefore difficult to find new solutions within the prevailing Western paradigm. Rebuilding an understanding of indigenous knowledge is essential to expand the collective imaginary and achieve the mutual benefits of a more resilient and symbiotic planet. Australian Aboriginal peoples are the oldest continuous civilization on Earth, with architectural proof of settlements dating back to 50,000 years. They have lived in tandem with nature for millennia, guided by certain worldviews that have allowed them to create sustaining relationships with their environments. There exists extensive, multigenerational, empirical knowledge, which has historically been dismissed by academia and tentatively effaced by settler society. This research aims to honor such knowledge by bringing indigenous discourses on sustainability into academia, and situate it within current applications for a more sustainable globalized world.

A systematic review of Indigenous knowledge and sustainable practices, and coded interviews with the Indigenous diaspora, allow a pluralistic approach to sustainable development and CE. Moreover, relevant concepts are operationalized in a qualitative system dynamics model to provide new insights on CE principles.

Capital, Energy, Water and Carbon in the Singapore Economy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Anthony Meijer [1], ***Lynette Cheah*** [1], ***Chris Kennedy*** [2]

1. Singapore University of Technology and Design, 2. University of Victoria

In economies, the accumulation of capital assets is associated with prosperity, growth and also environmental impacts. Among the types of capital assets are fixed assets such as buildings and infrastructure, equipment such as transportation equipment and machinery, and intellectual property products. Capital is formed and used to produce goods and services, and resources are invested in both forms. Knowing the nature of capital formation and asset stock helps in understanding the resource basis of the economy. The paper explores the relationship between capital assets, energy and water consumption, and carbon emissions in Singapore between 2010 and 2016.

Capital stock in Singapore has grown sevenfold. Most (81%) of these assets belong in the services and commerce sector. Yet, resource use has not been growing as quickly. Some decline in energy, water and carbon intensity of both forming and utilizing capital assets were observed. Meanwhile, capital formation in manufacturing assets has doubled in energy use and greenhouse gas (GHG) emissions. In fact, using assets in manufacturing is a few orders of magnitude more resource-intensive than in services. In the residential sector, the stock of property assets has also increased, but the resource intensity of constructing and using residential buildings has declined by 17% and 42% respectively. In comparison, energy intensity for capital formation and usage in the industrial sector is much higher than in the residential sector. The converse is true for water and carbon intensity. Overall, the intensity of capital formation is significantly higher than capital use at 95.6 TJ/$ million of investment for energy use and 3,690 tCO2e/$ million of investment for GHG emissions in 2016. Meanwhile the energy-intensity for capital use is 1.60 TJ/$ million of stock value. In spite of this, water intensity has decreased consistently in capital formation and usage of both residential and industrial assets.

It is clear that the services and commerce sector has become more efficient, with a negative correlation between resource use and asset growth. We note that the capital stock of Singapore is dynamic and therefore offers a great opportunity for decarbonization. In particular, the manufacturing sector can improve by adopting greener building and operations practices. Meanwhile, circular economy frameworks should guide the construction sector's sustainability agenda. The study presented here can be used to understand the resource nature of different industrial capital assets and guide the selection of investments and planning for future resource-efficient development pathways.

Building Design for Disassembly and Adaptability – LCA of Flexible Building Structural Systems

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Doreen Steven Mlote [1], ***Michael Budig*** [1], ***Lynette Cheah*** [1]

1. Singapore University of Technology and Design

Throughout their life cycle, buildings have an impact on natural ecosystems. Globally, buildings and construction processes emit 40 to 50% of greenhouse gases (GHG). The use of different materials during construction, maintenance, and refurbishment, as well as the emission of dangerous compounds during a building's life cycle, all directly influence its impact. To reduce the built environment's environmental impact, using sustainable, recycled and upcycled building materials, and circular design and construction methods have become the primary focus of research and development to achieve the objective of sustainable construction. This is one way the building industry can contribute to protecting the environment.

However, a building's post-use treatment has not yet been fully solved. There is a gap for researchers to re-evaluate ways to attain net-zero waste and emissions from construction materials and designs and the processes involved. Innovative construction methods have gained interest in an attempt to implement low-environmental impact strategies from as early as the design stage. Researchers have been connecting the choice of materials and processes/practices to the sustainability potential of buildings, particularly renewable materials such as wood. However, aside from choosing lower-impact building materials, buildings' longevity also matters. To achieve the goal of sustainable construction, the focus should not necessarily be on introducing buildings that are rigid and built to last, but to buildings that are adaptable to future demands.

There is growing interest in flexibility, physical redundancy, and reusability of buildings – potentially leading to a more adaptable and sustainable future for facilities, buildings and infrastructure. When a building, its layout or some of its components can be dismantled, modified or upgraded, methods such as Design for Adaptability (DfA), sometimes referred to as '*Design for Reuse*', allow the repurposing of buildings into newer functions hence offering a method to develop closed-loop material flow systems. However, the success of DfA methods relies on implementing these strategies from as early as the design stages.

To bridge the gap and find solutions that match the growing demands, a literature review was significant to analyse and assess all advancements that have been implemented so far and figure out how we can further improve and motivate the use of DfA methods. The findings from the literature review indicated that there is a growing demand for adaptable structures and lesser methods to validate or assess the designs for adaptability features early on. As a next step, we will investigate the extent to which building materials and installations can be reused and calculate the expected estimated savings. A Life Cycle Assessment (LCA) of flexible structural systems that can accommodate different building configurations per occupancy needs will be conducted. This requires an understanding of potential building uses, in order to predict the extent to which buildings (residential and commercial) need to adapt or have their lifetime extended in the future. This is significant as it will help postpone or entirely avoid the need for pre-mature building demolition and waste generation.

The findings from the LCA will provide insights on the potential impact of DfA concepts in building structural systems – highlighting the trade-offs between highly durable structural systems, functional flexibility, and sustainable, lower-carbon structural systems. This study aims to improve confidence on the implementation of DfA methods as a sustainable approach for building construction.

A new BIM-based method to promote Buildings Circular Economy at a neighborhood scale

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

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The adoption of Circular Economy (CE) practices may impact 30% of the natural resources used globally, as well as 25% of the amount of waste generated [1], or even to 50% of total energy use [2]. The application of CE principles in buildings refurbishment is timely, as 85% of European Union buildings were built before 2001 and 90% will still exist in 2050 [3].

However, the adoption of CE practices in buildings refurbishment at an urban level is still in its infancy, particularly because, to better define strategies for buildings refurbishment, detailed building characterization for all the urban building typologies is crucial and is lacking. Also, there is no clear methodology for calculating Circularity Indicators and Embodied Energy from early design stages, which hinders CE implementation.

This paper adopts an archetypes methodology [4] for energy assessment at an urban scale, which clusters buildings by their main use (residential or non-residential), construction period, size-class, roof type and neighbouring conditions. Structure type and exterior finishes layers were added to the existing archetypes methodology, to obtain data about materials and construction systems. This information is used to calculate their Circularity performance and Embodied Energy. The archetypes approach also helps to understand the potential for urban mining and material flows management, and facilitates the use of Geographic Information Systems (GIS) in the implementation of CE strategies.

To demonstrate the application of CE strategies in buildings refurbishment, this paper focuses on a specific building archetype from Lisbon, built between 1919 and 1945, which represents 8,236 similar buildings in the city. This paper uses a Building Information Modelling (BIM) software to compute the mass of construction elements and layers of this archetype as built. After characterizing CE data in Product Data Templates [5], Embodied Energy and Circularity Indicators were computed, according respectively, to [6] and [7],[8],[9]. Calculations cover material, product and system levels, considering disassembly indexes. The joint analysis of Circularity Indicators and Embodied Energy is used to identify the best refurbishment options for the archetype, based on the end-of-life of existing materials. This paper also examines three different renovation scenarios and their impacts on embodied energy: total demolition and reconstruction; interior structural refurbishment and space plan refurbishment.

It was found that the adoption of CE strategies can help to avoid total demolition of the building, saving 67% of embodied carbon. Additionally, it can lead to the recycling or recovery of materials such as brick, aggregates, and timber. The study also shows that the reuse of elements such as windows and doors can save a significant amount of embodied energy and reduce the overall impact of human activity in the built environment. The findings on this study can be used to define targets for reducing embodied carbon and implement policy-based incentives for CE adoption.

Overall, this study highlights the importance of understanding the characteristics of existing buildings and applying CE principles in their refurbishment. It also emphasizes the need for a combination of top-down and bottom-up approaches and the role of digital tools in the implementation of CE strategies in cities.

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Extended Producer Responsibility as enabler for circular value chain

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Xin Tong [1]

1. Peking University

This research explores the role of extended producer responsibility as the enabler of circular value chain in the context of China. The driven forces and key stakeholders are identified for extending producers responsibility in the development of the national circular economy strategies. An evaluation system was established to link the producer's eco-design strategy with the performance of downstream recycling of products. The eco-design information was retrieved from the self-disclosure information in the sustainable development report of the producers. The downstream waste flow information comes from multiple platforms of reuse and recycling companies. The aim is to establish an open forum for competition and cooperation among different stakeholders to achieve the continuous improving target of circularity and lifecycle environmental performance of products. With the evaluation results, the producers are encouraged to fully explore all opportunities in the circular value chain instead of focusing only on the final disposal or disassembly. The conclusion suggests that the policies are needed to break the restrictions on eco-design and innovation in business models through creating and capturing values of circularity.

Offshore wind energy and marine biodiversity in the North Sea: life cycle impact assessment for benthic communities

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Chen Li [1], ***Joop Coolen*** [2], ***L. Scherer*** [3], ***José Mogollón*** [3], ***Ulrike Braeckman*** [4], ***Jan Vanaverbeke*** [5], ***Arnold Tukker*** [3], ***Bernhard Steubing*** [1]

1. CML Leiden, 2. Wageningen Marine Research, 3. Leiden University, CML, 4. Ghent University, 5. Royal Belgian Institute for Natural Science

Large-scale offshore wind energy developments represent a major player in the energy transition but are also likely to have an impact on marine biodiversity. Offshore wind farm (OWF) replaces soft sediment with a hard substrate, occupying the seabed and creating an artificial reef for sessile dwellers. It furthermore leads to a decrease in (and even a cessation of) bottom trawling, as this activity is prohibited in many OWFs. The long-term cumulative impacts of these changes on marine biodiversity remain largely unknown. This study provides a framework for integrating such impacts (negative or positive) into characterization factors (CFs) for life cycle assessment (LCA) and illustrates it based on the North Sea. Results show no net adverse impacts during OWF operation on benthic communities inhabiting the original sand bottom within OWFs. The artificial reef effect could lead to a doubling of species richness and a two order-of-magnitude increase of species abundance. Seabed occupation will also incur in minor biodiversity losses in the soft sediment. Our results were not conclusive concerning the trawling avoidance benefits. The developed CFs quantifying biodiversity-related impacts from OWF operation provide a stepping stone towards a better representation of biodiversity in LCA studies.

The potential for missing middle to provide more housing with less embodied emissions: quantifying and optimizing material efficiency in low-rise, multi-unit housing

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Keagan Hudson Rankin [1], ***Aldrick Arceo*** [2], ***Kaan Isin*** [2], ***Shoshanna Saxe*** [2]

1. *University of toronto,* ***2.*** *University of Toronto*

This research addresses two critical problems facing cities today: a lack of housing for the world's growing urban population, and the need to reduce material consumption to mitigate the impacts of climate change. Specifically, this work investigates the potential of missing middle buildings (low-rise multi-unit housing) to provide housing with lower embodied Greenhouse Gas (GHG). Material production and use makes up 20-25% of annual global GHG emissions and must be reduce by at least 78 Gt-CO_2eq to meet the Paris Climate Agreement's 1.5°C target in 2060. At the same time, global increase in urban population is accelerating demand for housing. If future housing is built following current norms, climate commitments will be near impossible to meet. For example, the population of Toronto, Canada is expected to grow by 1 million (36%) in 25 years. Strategies for supplying more materially efficient housing are urgently needed to preserve human well-being without compromising sustainability goals. Here, we quantify the potential of missing middle for reducing the embodied GHG of housing, compare it to other residential forms, and identify opportunities for optimizing the material efficiency of housing. Detailed, bottom-up estimations of material quantities are newly calculated for 39 North American missing middle buildings after Guven et al., 2022, most of which are examples from Toronto. GHG emission factors for materials are calculated from local Environmental Product Declarations. We find that the embodied emissions of residential building have large variation between and within forms, ranging from 6,000 to 35,000 kgCO2eq/bedroom. A few major elements, particularly substructure concrete, XPS/polymer-based insulations, masonry cladding, and structural steel framing, account for on average 40-60% of total CO2eq in buildings. Single family homes use significantly more embodied emissions for many construction materials compared to missing middle buildings. If single-family homes in Toronto had the material efficiency of an average missing middle home, Toronto's embodied emissions would be reduced by 2.84 MTCO2eq (25%). Finally, our analysis shows that while missing middle is more materially efficient than single family or high-rise construction on average, the largest savings are found through a shift to best-in-class construction within any form.

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An economic complexity tool to analyze Circular Economy capabilities in global economy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ilaria Lombani [1], *Ilaria Giannoccaro* [1], *Luca Fraccascia* [2]
1. Polytechnic University of Bari, Bari (Italy), 2. Sapienza University of Rome, Rome (Italy)

Circular economy (CE) represents a new industrial paradigm aimed at overcoming the traditional "take, make, dispose" economic model and promoting more sustainable resource consumption patterns and production processes (Kirchherr et al., 2017). To support transition to CE, companies are called to change their mindset, their business models, and are required to develop CE strategies and implement effective CE initiatives. For this reason, they require new specific capabilities, properly fitting their features. In fact, a variety of new skills, resources, and capabilities are essential to design and pursue a circular future and effectively implement circular transition (Alix and Vallespir, 2010, Kopnina, 2014; Khan et al., 2020).

Coherently, in this paper we define CE capabilities as a combination of appropriate skills, knowledge, and abilities, glued together by various relevant organizational processes, routines, and bonding mechanisms, necessary to develop, adopt and implement the CE strategies successfully.

Since multiple CE strategies can be designed and selected, usually classified by the so-called "R" frameworks (Sihvonen and Ritola, 2015; Van Buren et al., 2016; Potting et al., 2017), we argue that any CE strategy requires a specific set of CE capabilities to be successfully adopted and implemented.

Thus, our research aim is to understand which CE capabilities are relevant for different CE strategies, if companies in a country possess the CE capabilities, and which CE strategies to pursue based on the possessed CE capabilities.

We address this research aim by adopting a capability-based theory approach (Teece et al., 1997) and relying on tools coming from complexity economics, used to capture the country's production capabilities (Higaldo et al., 2007) and green product capabilities (Fraccascia et al., 2018; Mealy and Teytelboym, 2020). The economic complexity approach captures information on the productive capabilities and production structure of the countries by making relative comparisons between the baskets of national exports (Hausmann et al., 2014, Hidalgo, Hausmann, 2009, Hidalgo, Klinger, Barabási, Hausmann, 2007). Thus, through this approach, it is possible to capture information about the specific CE capabilities possessed by countries (Country Circular Economy Capability Space). This information can suggest, based on a measure of similarity (Circular Economy Capability Proximity) between companies in a given economic sector and the CE capabilities associated with that sector, which CE strategies companies in that economic sector should adopt.

To build our CE complexity tool we use the data in EXIOBASE3 database, available on Zenodo. EXIOBASE3 provides a time series of multi-regional input output (MRIO) tables for 49 countries and 163 industries. We refer to 49 different countries and 163 sectors for the years between 2007 and 2021. For each country, we calculate the Country Circular Economy Capability Space, which offers a clear assessment of the CE capabilities of the country and the CE proximity index which on a global level measures the captures the similarity between the CE capabilities and the general capabilities possessed by an economic sector.

The paper contributes to classify and assess the level of CE capabilities of companies using a quantitative tool able to compare them across multiple countries and it provides managerial guidelines to companies belonging to different economic sectors about which CE strategies are most effective.

Prospective life cycle assessment of hemp fiber production versus glass fiber production

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Hanie Zarafshani [1], *Ponnapat Watjanatepin* [1], *Karel Van Acker* [1]
1. KUL

Although bioeconomy innovations may play an important role in supporting a more circular and decarbonized economy, it is critical to guarantee that these technologies deliver more advantages than burdens at an early stage of development. Furthermore, understanding and reducing trade-offs are critical for directing investment and technology innovations toward a sustainable economy. Assessing the environmental implications of technology and goods at an early stage is difficult, and this is also true for biobased products.
A substantial role is played here by prospective life cycle assessment. Although there are still some methodological challenges with the integration of scale and time, prospective LCA has grown more significant in the evaluation of the environmental implications of new technologies. To solve some of the aforementioned issues, scenario analysis was considered a key approach to doing the PLCA. Scenario analysis considers the environmental implications of technologies and their products in the future. It examines the future environmental impact of technology and its byproducts. Furthermore, scenario analysis will be used to examine several variables that influence the evolution of such processes.
The environmental performance of hemp fiber production was compared to glass fiber production at TRL 6 or 7 in this study using an exploratory scenario method for the different future (2030 and 2050) routes in Europe. Furthermore, combining a causal loop diagram with an LCA flow chart attempts to graphically relate the technical parameters, comprehensive-picture surrounding parameters, and the LCI model itself.
Because the deployment of bio-based product innovations is influenced by several technological and socioeconomic factors, developing future scenarios that are transparent, consistent, and trustworthy has proven difficult. To address these issues, a PESTEL scenario analysis was performed, taking into account numerous variables that affect the development of bio-based product processes, such as biomass availability, climate conditions, biomass feedstock availability, increase in technological performance, or substitution of virgin wood for biomass feedstock. Finally, the LCA results for the developed scenarios were computed using the future's background database.
The comparison of the GWP of future hemp production and the GWP of current production revealed that the global warming potential can be reduced by up to 80% if society achieves the ambitious target of the Paris Agreement (+1.5 °C of atmospheric temperature increase by 2100) and the efficiency of hemp production technology increases by 10%. Furthermore, the results suggest that even in the worst-case scenario for the future (+3.5 °C of atmospheric temperature increase by 2100) and with no improvement in hemp production efficiency, hemp fiber production may be deemed more environmentally benign than glass fiber production.

The MRV Guidelines for Agricultural Products with Life-cycle Perspectives for Sustainable Agriculture

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Solhee Kim [1], ***Jung-Hun Song*** [1], ***Hakkwan Kim*** [1], ***Jeongbae Jeon*** [2], ***Kyo Suh*** [1]

1. Seoul National University, 2. Spatial Information Research Institute

The importance of the MRV (Measure, Report, and Verification) system on the implementation of carbon reduction measures by sector is being raised to achieve the 2050 carbon neutrality target. However, Korea's agricultural sector has yet to have an MRV for cases that apply technologies and methods to reduce greenhouse gas emissions. Moreover, to achieve the 2030 NDC submitted to the international community, we need to establish accurate statistics at the Tier 2 level or higher to respond to sector-by-sector and year-by-year inspections of greenhouse gas reduction targets and implementation status. Therefore, we would like to present MRV guidelines to assess the implementation of accurate carbon emission calculations and reductions in the agricultural sector. To this end, we conducted a case study on the development of MRV guidelines for each agricultural sector emission source and reduction means in developed countries. Based on these case studies, we reviewed the applicability in Korea and developed a verification methodology. We conducted an LCA evaluation of sweet potato cultivation in Korea and estimated the greenhouse gas reduction effect when greenhouse gas reduction means were applied during the cultivation stage. For this developed verification methodology, we intended to prepare circuiting systems for third-party review, performance inspection demonstration, and evaluation.

Teaching Industrial Ecology Through Disasters: Analysis of Student Reflections

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Wissam Kontar* [1], *Andrea Hicks* [2]**

1. University of Wisconsin-Madison, 2. Wisconsin

In this work, we analyze student reflection data on their teaching experience from a class dedicated to teaching engineering systems, uncertainty, and tradeoffs by exposing students to notable historical engineering disasters. Student reflections were collected from two consecutive semesters. In total, 83 short reflections (on average 100 words in length), and 61 long reflections (on average 1,000 words in length) were collected. A Latent Dirichlet Allocation (LDA) model was formulated with a Bayesian probabilistic approach in mind to analyze the large text-based reflection data. The LDA model was used to discover short semantic structures (topics), and measure how closely each student's reflection is relevant to the discovered topics. Eventually, themes – a collection of topics – were extracted to draw conclusions about students' learning experiences.

The analysis shows the connections students built between engineering failures and its multi-faceted implications. Ultimately, this teaching framework can guide engineering class design that embraces real-life failures as avenues of education.

A conceptual model for linking wellbeing and prosperity to service provision in the energy service cascade

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Stefan Pauliuk [1]

1. *Freiburg University*

Decoupling wellbeing from material and energy consumption via so-called demand-side solutions is a crucial lever for sustainable development (Creutzig et al., 2018). To develop effective policies and business models to support demand-side solutions, a deep understanding of the link between personal wellbeing, societal welfare, and consumption of products and services is needed. In current IE models, such as the energy service cascade (Kalt et al., 2019), no detail regarding how exactly service provision links to wellbeing (individual level) and societal prosperity is included.

Here, a conceptual model for linking wellbeing and prosperity to service provision is presented and a first attempt to quantifying this model for specific regions and scenarios is undertaken.

We start from three observations:

(1) Final demand y can be broken down into different consumption categories (Brand-correa et al., 2020). We model y = y_DLS + y_Habitual + y_Competition + y_Luxury. Here, DLS stands for 'decent living standards' and denotes the consumption needed to satisfy basic needs. The different consumption types have different drivers and levers for change (e.g., luxury: brutal taxation, competition: Gini coefficients, habitual: behavioral change), and different contributions to wellbeing.

(2) A minimum level of consumption is needed to satisfy basic needs, given by the consumption needed to deliver decent living standards (Millward-hopkins et al., 2020; Rao and Baer, 2012).

(3) There is a strong link between certain consumption patterns and societal inequality, so-called status or competition-related consumption, such as the desire for certain types of housing and cars, and we postulate that there is a relationship between the Gini coefficient for expenditure and the magnitude of y_Competition.

Based on these hypotheses, a multi-disciplinary literature review is undertaken to establish conceptual and empirical linkages between different consumption groups and wellbeing/welfare and between wellbeing (personal level), welfare (society level), and inequality (measure by the Gini coefficient for income inequality).

A conceptual model for final demand will be developed, linking average per capita final demand to a Lorenz curve for expenditure that is governed by only two parameters: the ratio between average per capita consumption and DLS per capita consumption and the Gini coefficient of expenditure. This way, the two major inequality descriptors within-country inequality (expressed as Gini coefficient of expenditure) and between-country inequality (expressed as ratio between average per capita consumption and DLS per capita consumption) enter as parameters a final demand model that produces an average per capital final demand vector.

The poster will present the literature review and the conceptual model in concise form and will show how this model can be applied to build scenarios for demand-side solutions in the energy service cascade in prospective industrial ecology and integrated assessment models.

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Efficiency Implications for Construction Material Use under Demographic Change – Case Study Evidence

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Andreas Blum [1]

1. Leibniz Institute of Ecological Urban and Regional Development

Housing and construction have a significant impact on the consumption of resources of any society. At the same time, on all policy levels strategy documents towards sustainability highlight the importance of improvements in resource efficiency. Against this background, this contribution presents results of research on the impact of demographic trends and changing user preferences on the use of resources within the housing sector with a focus on construction materials. The material intensity of different types of housing (in particular detached homes vs. apartment buildings) are quantified for different housing scenarios. For comparative purposes two medium sized German case study municipalities were selected to represent different contexts of stable vs. declining population development. Among other, the results indicate that the stock of construction materials incorporated within the housing sector will under trend conditions further increase despite a stable or even falling population. With respect to alternative housing scenarios, our results show, that in the case of a stable or slightly growing population a sufficiency oriented shift of housing supply from single-family (detached) homes towards a higher share of multi-unit residential buildings can contribute to a more efficient use of materials (stock of construction materials per capita). However, depending on the context, such a shift towards more sufficient individual housing models might nevertheless result in an overall increase of material intensity on the level of the municipality. This is due to increasing vacancy rates in the single family home segment with the respective embodied materials being wasted. An interesting scenario under the context of a declining population is the conversion of a potentially growing number of vacant single-family homes into smaller multi-unit/multi-purpose residential buildings. Such a conversion can help to avoid vacancy and keep otherwise wasted resources in use. This scenario could gain even more practical relevance if future detached housing designs would intrinsically consider the option of a later division into smaller residential units – apartments – e.g. once the children moved out or elderly households wish to downsize their living space and likewise maintenance burden.

Wellbeing provided by the building stock in Trondheim: Service level and service accessibility

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

JiaJia Li [1], ***Mark Uwe Simoni*** [1], ***Nils Dittrich*** [1], ***Daniel B. Müller*** [1]

1. *Norwegian University of Science and Technology*

Identifying pathways for wellbeing within planetary boundaries is a key challenge for humanity. The development of the building stock is critical for both as it provides service essential for wellbeing while it also contributes to the alterations in the environment such as resource depletion, climate change, or biodiversity loss. In addition, the location of different types of buildings is critical for urban quality and the need for transport, with further environmental consequences. Previous studies have analyzed the environmental impact of the building stock, while its roles in different aspects of wellbeing remain poorly understood. Here, we analyze the service level of residential and non-residential buildings in different neighbourhoods in Trondheim. We further study the accessibility of essential services in the neighbourhoods using information about the function of the buildings and the geographic location. Both, service level and service accessibility are quantified using indicators and analyzed in terms of inequality between neighbourhoods. The tool for exploring wellbeing is combined with tools for analyzing environmental impacts. The combination of the two allows informing strategies on wellbeing within given environmental boundaries in a more differentiated way.

Provision of housing services within planetary limits: a methodological framework for the urban circular economy

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Ankita Singhvi [1], *Aristide Athanassiadis* [1], *Claudia R. Binder* [1]
1. HERUS Lab, EPFL

The provision of decent housing for all is a core sustainable development goal (SDG) and a fundamental human right. However, the construction sector is the world's largest consumer of raw materials, and 40% of global CO_2 emissions are attributed to housing and construction. The challenge of providing decarbonised and decent housing differs per urbanisation context. In rapidly developing cities, there is the question of how to build decent, affordable housing that meets human needs without locking the city in resource dependency and negative climate impacts. In aging cities, there is the question of how to reduce the emissions and material use of old building stock. The circular economy proposes strategies to close material loops, minimize harmful resource use and cease local waste generation. However, meeting housing needs within climate targets requires consideration of more than material and energy stocks and flows. There is a paucity of attention for social dimensions and clear targets in monitoring the circular economy.

We propose a methodological framework to articulate the provision of housing services within planetary boundaries by implementing circular economy strategies. It consists of four elements.

First, the *material system of stocks and flows*. The stock characteristics relevant to the provision of housing are building typologies, their related materials, age, area and height. The relevant flows are construction materials, operational energy, demolition materials, and direct emissions. The material system can be modelled and analysed using material flow analysis.

Second, *the social system* that influences and is influenced by the construction, operation and demolition of buildings. The social system consists of agents, their actions, and the structural factors that act on them. Agents are actors related to each stock and flow. Agents relevant to the provision of housing are architects, constructors, clients, developers, etc. Structural factors draw on Gidden's structuration theory, and are made up of rules and resources such as building codes, cultural norms and power relations. Actions are the circular economy practices that the agents choose to do: repair, renovate, re-use, recycle. The social system is analysed with structural analysis using data from interviews, surveys and/or workshops.

Third, the material system and social system act together in the provision of *services* related to housing: living space (m^2), warmth (RC in m^2K/W), access to amenities (amenities/km^2), etc. These are elicited based on the analysis of the material and social system.

Fourth, the *assessment* of the housing system's ability to meet needs within planetary boundaries. The services required to fulfill the provision of housing are not universal; they depend on the needs of the actors. A dwelling may fulfill one or many needs: e.g. security of tenure, affordability, habitability, location, cultural adequacy, etc. Furthermore, the provision of services has consequences for the ability to stay within planetary boundaries: which may be defined in relation to climate targets, biosphere integrity, land-use change, etc. This is monitored with the use of biophysical indicators (i.e. carbon and material footprint) and well-being indicators, using life cycle inventory and survey data.

In conclusion, the proposed methodological framework builds upon Industrial Ecology and circular economy scholarship, and complements it with social consideration to respond to the central and urgent question: how to provide decent housing within planetary boundaries.

The effects of social life cycle aspects on the criticality assessment of Lithium

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Julius Ott [1]

1. *Graz University*

Material criticality, as one of the core issues of Industrial Ecology, is becoming increasingly important in a world in turmoil. However, the methodology to assess material criticality is not standardized yet, which can lead to ambiguous results. The current approach of the European Commission defines raw material criticality as a consequence of supply risk (SR) multiplied with economic importance (EI).

The hypothesis is that social aspects affect raw material criticality through altered SR and also have an impact on raw material criticality besides the two mentioned factors SR and EI. To avoid double counting, a new formula with sustainability aspects (environmental and social) as a third multiplication factor is proposed. To test the hypothesis, the study uses the case of Lithium to execute a criticality assessment according to the state of the art (European Commission) and then looks at different options to include social implications in the calculation of raw material criticality.

Challenges are the availability of data and the clear cause and effect attribution of the positive and negative social aspects on criticality, as well as the weighting of social aspects compared to “hard factors” such as, e.g., the substitution possibility. Preliminary results propose a need to include social aspects, but should be validated through more data. Further research could apply the method on other materials or include further aspects into the calculation.

Environmental Analysis of Returnable Packaging Systems in Different eCommerce Business Models and Returnable Packaging Management Models: Canadian Case Studies

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Jonghun Park [1], ***Zuha Waqar*** [1]

1. *Toronto Metropolitan University*

There is growing environmental concern regarding the increasing quantity of packages in retail eCommerce. This study investigated the environmental impact of two returnable packaging formats, performing life cycle assessment (LCA) case studies based on the Canadian apparel eCommerce market. In case study 1, the brand owner sold and shipped its products to final consumers using an expendable mailer and a returnable mailer that was managed and supplied via the centralized model. In case study 2, the brand owner rented its products to final consumers and shipped them using an expendable corrugated paperboard box and a returnable box that was managed and supplied via the decentralized model. Comparative, contribution, and sensitivity analyses were conducted to analyze and compare the environmental performance of these packaging options. For case study 1, the LCA revealed that the returnable mailer had greater impact than the expandable mailer in nine of ten environmental impact categories, even if the returnable mailer was reused for 40 cycles and the final consumer was in the same city as the brand owner; this was primarily due to the length of transportation. For case study 2, the returnable box had smaller environmental impact than the expendable corrugated paperboard box in six of ten environmental impact categories, even though the brand owner shipped packages to final consumers 9,000 km from its location. The overall results imply that the environmental burden of returnable packaging is primarily affected by total trip distance and the number of reuses. In addition, returnable packaging could have a competitive environmental advantage if the brand owner uses the subscription-based rental business model and supplies and manages returnable packaging via the decentralized model.

A multi-scale model of the environmental impacts of low-carbon construction in the City of Montreal

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Felicity Meyer [1], ***Benjamin Goldstein*** [1]
1. *McGill University*

Deep decarbonization of buildings and construction is required to reduce the 40% of global carbon emissions produced by this sector. Mass-timber construction that substitutes carbon-capturing wood for carbon intensive materials like steel and concrete can assist in this transition. However, most studies of material use and embodied carbon in the built environment are deficient in that they rarely analyze the city-scale and they seldom capture connections between the city and hinterlands that supply most construction materials. As such, we lack knowledge to effectively decarbonize new construction in cities and do not know the potential impacts, such as deforestation, of large-scale mass-timber construction in cities. We address these knowledge gaps through a city-wide assessment of three key construction materials - steel, concrete, and wood - in the city of Montreal, Canada. We combine bottom-up material accounting of the building stock with life cycle assessment to analyze the carbon emissions and land change implications of future development scenarios in the city. We compare the "status quo" construction reliant on concrete and steel to the use of renewable, regionally available materials, such as mass timber at the neighborhood and city scales. This study provides much-needed insights to aid the construction sector in strategically implementing low-carbon development that decreases the environmental impacts of urbanization both in cities and in their hinterlands.

An industrial symbiosis and synergy matching information tool using company-level waste inputs and outputs in Taiwan

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Pi-Cheng Chen [1]***, Kuan-Wei Li*** [1]***, Kun-Hsing Liu*** [2]

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Many cities and industrial parks have considered industrial symbiosis a promising development model to reduce waste generation and gain the economic benefit of saving virgin materials costs. As the synergies emerged in Denmark's Kalundborg industrial park, one factory might use the byproduct from another factory in an eco-industrial network. To accelerate the matching of synergies, several information systems were developed. The richness and detailedness of data determine the application of an information tool. Therefore, very few information tools can be applied to many potential geographical areas like the SYNERGie® supported by the National Industrial Symbiosis Program of the UK. The PURE lab at National Cheng Kung University developed an information system rich in company-level data by using the outputs and inputs of industrial waste with a very detailed waste classification of Taiwan EPA. The company generating wastes and the companies of potential to reuse are matched using the list of waste outputs and waste inputs and measuring the proximity. A web app has been developed for authorized users to match. There are three kinds of user interfaces. The first one can show the distribution of sources of one selected waste and companies using that waste as inputs. The second interface can search the companies that were using the wastes and the companies of potential to reuse in the selected city or county. The third interface can analyze the potential eco-industrial network for industrial parks. Using this tool, we have discovered the synergies emerging from exchanges of byproducts between industrial parks.

Sectoral Coordination Maximizes China's Provincial Building GHG Emission Mitigation

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:28: Mitigation Policies (short presentations) (A1.44 KOG)

Qiance Liu **[1]*, Kairui You* [2]*, Xin Ouyang* [3]*, Weiguang Cai* [2]*, Gang Liu* [1]**

***1.** University of Southern Denmark, **2.** Chongqing University, **3.** University of Chinese Academy of Sciences*

The increasing building stocks and associated material and energy consumption have contributed to one-fifth of global greenhouse gas (GHG) emissions. Achieving climate goals relies on a higher-resolution building GHG emission result to guide local building decarbonization, especially for those large countries like China. As the largest building GHG emission emitter, China is about to reach the "turning point" when the boom of new buildings calms down and the large-scale renovation starts. Therefore, China may face double challenges in its low-carbon building transition efforts in the next decade: the accelerating construction of new buildings for developing countries and the renovation of existing buildings for developed countries.

The recent years have seen an increasing body of literature on building GHG emission modelling and mitigation strategies discussion, including for China. However, how the renovations will impact building decarbonization has not been explicitly presented yet for China. At the same time, few studies considered the regional disparities in operational and embodied GHG emissions associated with Chinese buildings.

Here we aim to address these knowledge gaps by developing a Building-Material-Energy-Emission (BMEE) model that includes a novel renovation module to assess CO_2 emissions and mitigation potentials from buildings in mainland China on the province level from 2000 to 2060. We further developed different scenarios for emission reduction, with the recently released policies from the Chinese government selected as benchmarks.

We show that CO_2 emissions from Chinese buildings are expected to peak the latest by 2026, and up to 61.6 Gt CO_2 can be mitigated in the next forty years. The five dominant strategies (i.e., urban renewal, green building, low-carbon construction, circular economy, and energy transition) will make significant but various contributions to China's national and provincial building decarbonization under the current policy options. More comprehensive and deep building decarbonization strategies, particularly, need coordination from all related sectors. Our results could provide concrete and accurate implications in guiding Chinese buildings' GHG emission mitigation and call for more attention to the upcoming "Renovation Wave" in China and the world in the post-pandemic age.

Teaching life cycle assessment using counter intuitive examples

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Andrea Hicks [1]

1. Wisconsin

In sustainability there is “no such things as a free lunch”, not only economically but also environmentally. Everything product and process has an environmental impact. However, often perceptions of which product is “more sustainable” is clouded through preconceived notions and greenwashing. There are a multitude of examples withing the life cycle assessment (LCA) literature, particularly focusing on products of consumer convenience: single serve coffee pods , kitchenware, meal kits, etc.. The term “counterintuitive sustainability” will be used herein to describe products which are commonly thought to have a higher environmental impact by the general public, however, when studied through LCA actually are less environmentally impactful.

A graduate project based course on LCA was centered on the “counterintuitive sustainability” example of single use plastic drinking straws compared to other single use drinking straws and multi use drinking straws. Students selected a project within the general topic of the environmental impacts of drinking straws, with some focusing on fewer products and a cradle to grave perspective while others focused on materials in a cradle to gate perspective. Drinking straws are one such example of counter intuitive sustainability. LCA can be used to reveal the truth of the environmental impact of a product or suite of products, regardless of the popular preconceptions of what is sustainable. There has been a great deal of popular media coverage around the environmental ills caused by single use plastic straws. This was particularly true in the 2015 viral video where a plastic straw was pulled out of a sea turtle’s nose by a then graduate student. Which then sparked a cascade of advocacy to ban single use plastic straws, and a flurry of potential single use plastic straw replacements. Subsequent LCIAs of single use plastic straws and their alternatives have shown that when compared to the replacements, in many environmental impact categories, the single use plastic straws are the better option. In particular, reusable straws depend a great deal on human behavior which is challenging to quantify adequately in LCA. Also, there are considerations beyond environmental impact as well, such as people with disabilities who require straws for drinking beverages safely.

In order to gain insight as to the students’ prior level of sustainability and life cycle assessment knowledge, along with their preconceived ideas of which straws had the least environmental impact, a pre-course survey was administered. The same survey was again administered at the end of the course, which allows for better understanding of how the students’ perceptions of their own knowledge changed. The students also completed a course reflection at the end of the semester comparing and contrasting sustainability with LCA, and what the role of LCA is within sustainability. Many of the students came in with a preconceived notion that sustainability and LCA were one in the same. Analysis of the pre and post surveys illustrated a greater literacy gained by the students throughout the course, and an increased skepticism of the idea that all single use products have a greater environmental impact than there reusable counterparts.

eCommerce Value Chain Analysis in Reverse Logistics - Economic and Environmental Comparison

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Shira Shabtai [1], ***Rotem Rotem*** [1], ***Tamar Makov*** [1]

1. *Ben Gurion University of the Negev*

The eCommerce industry has seen dramatic growth over the past few years. As the share of products sold online continues to grow so do return rates, presenting economic and environmental challenges for both retailers and consumers. The current assumption is that online returns cost retailers trillions of dollars and are associated with large environmental impacts. Smart management solutions provided by reverse logistics companies aim to improve both economic and environmental performance and generate a win-win solution for both customers and companies. We ask to examine these two statements; Relying on a unique dataset provided by industry partners, we mapped the flows of returned products across different post-return pathways. Focusing on apparel, we assessed the economic costs and the environmental impact associated with online product returns, and examined potential tradeoffs between the two. Our goal is to shed light on the hidden environmental costs of product returns, give a broad overview of the decision making economic- environment tradeoffs and finally propose ways by which they can be mitigated.

Life cycle assessment of high-value biochemicals: systematic review and recommendations

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Sunday, 2nd July - 17:45: LCA case studies 2 (B0.31 KOG)

Shiva Zargar [1], *Qingshi Tu* [1]

1. The University of British Columbia

The environmental concerns associated with the petrochemical industries resulted in the increased research and development of processes in which bio-feedstock can be converted into chemicals. The term “bio-based” is not always synonymous with “environmentally friendly”, mostly when less well-known impact categories such as water depletion, and land use are considered. Although the environmental benefits of biochemicals are largely unclear, they are gaining prominence due to the strong support of governmental policies and environmental regulations. Hence, understanding the trade-offs and synergies among the production of various biochemicals from an environmental perspective is necessary. Hence, a literature review is conducted to understand the extent to which life cycle assessment (LCA) studies are available for high-value biochemicals, to analyze the LCA methodology used in these publications, to understand the efforts that other researchers have done, and to find out a trend among LCA studies of different biochemicals. This study focuses on the top 30 high-value biochemicals recommended by National Renewable Energy Laboratory (NREL). In total, 65 peer-reviewed publications are found that focus on LCA studies of biochemicals. The results showed that the LCA of 22 biochemicals is available in publications or databases. For biochemicals with no LCA studies, the LCA models need to be created using approaches such as a similarity-based method for proxy selection, process simulation, and theoretical methods. All available LCA studies considered evaluating global warming potential (GWP) and 66% considered evaluating fossil fuel consumption and depletion impact categories. Even though water and land use are important elements in biomass production, they are barely reported in publications. A significant variation in GWP of biochemicals production is observed; such as levulinic acid (ranging from 6.30 to 250 kg CO2 eq per kg levulinic acid), and lactic acid (from -4.20 to 64.50 kg CO2 eq per kg lactic acid). This significant range of results routed in several reasons, including 1) different feedstock, 2) different production pathways (standalone production or in an integrated biorefinery system along with biofuels), 3) different processes (e.g. fermentation, catalyst application, or continuous versus fed-batch system), 4) choice of system boundary such as including distribution location (e.g. abroad versus local), and 5) including or excluding biogenic carbon credit. Overall, most GWP results fall between 0 and 5 kg CO_2 eq per kg target biochemical. For biochemicals having petrochemical counterparts, the comparison results show that there is a significant overlap in GWP results between biochemicals and petrochemical counterparts. It is vital to develop a standardized method in which specific guidance is provided regarding the choice of the system boundary, allocation method, and handling of biogenic carbon to support the creation and comparison among biochemical production and assist decision-makers in choosing the right biochemicals and production pathways to achieve sustainability.

Net-zero transition of the chemical industry: framework and results

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:14: IE and Industry (short presentations) (B0.31 KOG)

***Amrita Sen* [1], *Vyom Thakker* [1], *George Stephanopoulos* [2], *Bhavik Bakshi* [1]**

1. The Ohio State University, 2. The Global Kaiteki Center, Arizona State University

The anthropogenic emission of greenhouse gases to the environment must be reduced to net-zero if the ill-effects of climate change are to be contained. The commitments of industries and governments to this transition, while well-meaning, are often unsubstantiated by tangible strategies.

The chemicals and materials industry (CMI), though hard to decarbonize, is the key to net-zero transitions for other sectors. Thus, establishing net-negative emissions for the global CMI is critical. An array of technologies is being employed to enable this transition. However, in the absence of rigorous methods for evaluation and design, the path to net-zero remains ambiguous and the chance of burden shifting along the life cycle remains strong. Considerations like investments into research and development, synergistic emissions abatement of multiple technologies, dependence on background emissions etc. dictate the economic and environmental feasibility of technological choices in the value-chain. The current literature in the area focuses mainly on mature technologies. We build on this by including low technology readiness level (TRL) technologies within the life-cycle network superstructure to design temporally resolved net-zero, sustainable, circular value chains for chemicals and plastics.

A network model for the global chemicals and plastics production forms the basis of our framework. We model chemical processes at the value chain scale across life-cycle stages i.e., the transformation of fossil resources to platform chemicals, intermediates, fertilizers and polymers. The resulting life-cycle network may be parsed to yield a mapping of material flow across the supply chain. We supplement this network with data for emerging technologies such as the renewable power, carbon dioxide capture, electrified heating, the use of biomass-based feedstock, the electrochemical conversion of captured carbon dioxide to platform chemicals, recycling of plastics, and landfilling alternatives such as pyrolysis and incineration. We also allow functional substitutability between products. These models together constitute a superstructure network containing alternatives at all steps of the value chain. The underlying data are represented using the life-cycle assessment framework while the recently developed sustainable circular economy framework is used to handle circular flows. We develop a costing framework to estimate operating costs associated with emerging technologies, based on displacement at current product costs. We constrain the linear scale-up of bottom-up processes to meet the growing global demand of chemicals at discrete time steps. We model the evolution of TRLs according to experience curves. Stochastic effects as well as those of investment decisions on TRL evolution are incorporated. Additional constraints are levied to ensure the adoption of a technology only when it is sufficiently mature. The problem is formulated as a multi-objective optimization at discrete time steps where the set of allowed technologies, the final demand of products, the capital for investment, and the availability of natural resources and renewable electricity evolve with time and the system must reach net-zero emissions by a specific year, while minimizing capital, operational and investment costs.

Our results show that a combination of energy decarbonization and material recycling must be leveraged to reach net-zero. Material circularity allows for greater value addition while net-negative technologies such as biomass-based production offset emissions. Low TRL technologies allow greater value addition at lower emissions, subject to funds for their research and development and the availability of renewable power. Our roadmapping framework incorporates stochastic and economic considerations in decision-making processes, allowing the insights thus gained to guide the transition to net-zero.

Fingerprint 2 Footprint: Enhancing environmental sustainability of animal feed production by combining NIR spectroscopy and environmental footprinting

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:14: Food Systems (short presentations) (B0.41 KOG)

Maria Cairoli [1], ***Anne Ottenbros*** [2], ***Sin Yong Teng*** [1], ***Mark Schoot*** [3], ***Steef Hanssen*** [4], ***Christiaan Kapper*** [3], ***Rosalie van Zelm*** [4], ***Mark Huijbregts*** [4], ***Jeroen Jansen*** [1]

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Motivation and aim: The necessity of incorporating environmental criteria in decision making is increasingly recognised by stakeholders. However, environmental considerations are not always in synergy with economic profit. A better understanding of potential synergies between reducing both economic and environmental costs may therefore lead to more sustainable production strategies and win-win situations. The aim of this study is to explore the relationship between economic and environmental costs of animal feed production recipes and whether synergies are possible. We do this by combining NIR spectroscopy, chemometrics and in a complementary tool to optimize recipe formulations while enhancing the economic profit, lowering the environmental footprint and maintaining quality standards.
Approach: Animal feed recipes contain a combination of different raw materials (i.e. crops), grown at various origins and processed at different locations. NIR spectroscopy allows for non-destructive, cost- and time-efficient, and accurate characterization of the nutrient composition of crops. The accuracy of NIR spectroscopy allowed prediction of the origin country of crops based on the nutrient composition. Country specific environmental footprints, expressed in terrestrial ecosystem quality loss (EQL) and climate change (CC), were calculated by combining life cycle assessment (LCA) data of agricultural practices, regional yield and regional lost carbon sequestration capacity of natural vegetation (i.e. foregone sequestration). Regional data was used and subsequently grouped country specific footprint distributions. This information was combined with time-varying crops' prices in a stochastic multi-objective optimization to obtain a set of optimal formulations (i.e. pareto front) with minimum price and environmental impact. The optimization model included nutrient constraints to guarantee feed quality.
Preliminary results and relevance: The obtained pareto front from the optimization model results in recipes for feed formulations with both lower economic and environmental costs compared to benchmark recipes. Using variability in prices and environmental impact per country and crop type, and accurate nutrient compositions of crops from NIR spectra as a basis for feed formulations, our approach provides a realistic and robust view of possible variation. This results in country and crop specific recommendations for recipe formulations, which in turn can help companies to make decisions to achieve environmental and quality targets without additional costs. These results show that our unique approach of combining accurate NIR spectra with chemometrics and LCA works and recipes with high synergy between economic and environmental costs are obtained.
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Estimating dissipative losses in thermal spray applications: The current status and circular economy recommendations

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 15:45: Advances in MFA methods 2 (B0.17 KOG)

Mohamad Kaddoura [1], ***Guillaume Majeau-Bettez*** [1], ***Ben Amor*** [2], ***Manuele Margni*** [1]

1. CIRAIG, Polytechnique Montréal, 2. LIRIDE, Université de Sherbrooke

Thermal spray, which is a family of surface engineering technologies, is necessary in order for various components to meet technical functionalities under harsh environmental conditions. A thin coating material with the desired properties is applied to the substrate of the component to protect it. This technique comes at the expense of dissipative losses of coating materials throughout the life cycle of components. Some of those materials are considered critical due to their high economic importance, limited availability of viable substitutes, and supply risk. Measuring the share of these material life-cycle losses, which are usually high, has so far retained little attention in literature despite an abundance of parameters and characteristics of thermal spraying processes based on lab results. Accordingly, having a structured way to estimate the dissipative losses is needed.

This study applies substance flow analysis of the main metals used in thermal spray (Cr, Co, Mg, Mo, Ni, W, Y and Zr) to quantify their life-cycle dissipative losses. The investigated sectors are transportation (vehicles and aircrafts) and energy (gas turbines, hydropower plants and biomass plants) where thermal spray is highly utilized. Due to the scarcity of primary data, we strongly relied on experts' knowledge to balance mass flows of coating materials over the components' life cycle. This is complemented with an uncertainty range based on the pedigree matrix to account for the variability. Building on those results, material efficiency strategies specific to thermal spray applications are recommended to reduce the dissipative losses.

Preliminary results show that the life-cycle stage responsible for most of the dissipative losses is the coating itself, where real deposition efficiencies communicated by experts were much lower than what is usually reported in literature. Significant dissipative losses also occur at the end-of-life, where most coating materials are melted with the substrate (non-functional recycling) and not separated beforehand. Losses that occur during the use phase (e.g., by wear or corrosion) are negligible. Improving the deposition efficiency, recovering the unstuck coating and de-coating the components at their end-of-life were found to be key areas of intervention to reduce the critical material losses.

The parametrized framework provided in this study could be a basis to estimate the dissipative losses from other surface engineering technologies in the future.

Critical raw materials demand for green & digital pathways in Spain

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:35: Critical Raw Materials 2 (short presentations) (A0.51 KOG)

Martin Lallana [1]***, Jorge Torrubia*** [1]***, Alicia Valero*** [2]

1. CIRCE Institute – University of Zaragoza, 2. CIRCE Institute – Universidad de Zaragoza, Spain

A low-carbon economy is a material-intensive economy. Consequently, the mineral and material dimension of the energy and digital transition has received increasing interest in recent years . At the European level, concerns about the security of supply chains and the economic importance of different materials have led to the development of a list of critical raw materials since 2011. This list, updated every three years, has been growing steadily. And it is expected to continue as the demand for more quantity and variety of raw materials for the energy and digital transition increases. By 2020, it already accounted for 30 minerals and groups of minerals. This situation has driven policy changes in the European Union, such as the support for onshoring mining within member states (European Commission, 2020). However, the adaptation of these strategic plans to the Spanish framework has not been accompanied by a specific study of future mineral demand. This opens an important gap that needs to be filled. At the same time, Europe leads the Waste Electrical and Electronic Equipment (WEEE) generation per capita worldwide. Spain generated 19 kg per capita in 2019, far from the 2.4 or 7.2 generated by emerging powers such as India and China respectively (Forti et al., 2020). Despite this promising supply potential, there is hardly any specific study of the possible recovery of secondary raw materials from this high-value technological waste.

Therefore, our analysis sets out two main objectives for the specific case of Spain. First, we perform a detailed estimation of the future mineral demand associated with the energy and digital transition according to the already approved strategic plans and public policies. To this end, we work on government energy transition documents with a 2030 and 2050 horizon, as well as on strategic plans for energy storage and on strategic projects for economic recovery and transformation associated with the Next Generation EU funds. By applying a series of assumptions on the technologies used, material intensity and recycling rates, we obtain an estimate of future mineral demand for the specific case of Spain up to 2050.

Secondly, we make an approximation of the amount of secondary raw materials that could be recovered from the collection and recycling of WEEE. For this purpose, we apply a highly disaggregated analysis working with data from 43 categories of EEE placed on the market, following the UNU-Keys classification and considering a distribution of lifetimes. In previous research, the results showed the enormous opportunities for urban mining in Spain: the EEE placed on the market between 2016 and 2021 contains 1.4 million tonnes of metals, of which 20,000 tons are critical metals (Torrubia et al., 2023). Through this analysis, we project these results to a time horizon of 2050, based on certain assumptions regarding the degree of digitalisation, the WEEE collection capacity, and the degree of efficiency in recycling the raw materials contained in them.

Through these two calculations, we approach a specific picture of the mineral implications of the energy and digital transition currently at the center of public policy making. From the results obtained, we conclude with some recommendations for policy makers to ensure maximum sustainability and achieve a more circular economy that minimizes waste and secures the supply of critical raw materials.

Product obsolescence: relationships with product lifetime, product type, and household characteristics

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Monday, 3rd July - 12:14: Consumption, Policy, and Products (short presentations) (C0.06 KOG)

Haruhisa Yamamoto [1], ***Masahiro Oguchi*** [1], ***Daisuke Nishijima*** [2], ***Shinsuke Murakami*** [3]

1. *National Institute for Environmental Studies,* ***2.*** *Fukushima University,* ***3.*** *The University of Tokyo*

Premature product obsolescence is a major barrier to product lifetime extension and, ultimately, to a circular economy. A detailed understanding of the current situation of product obsolescence and its potential factors is essential; therefore, two distinct empirical studies regarding electrical and electronic equipment (EEE) were conducted. The first study investigated the differences of the lifetimes of EEE across different obsolescence reasons, specifically product failure and relative obsolescence (consumers' decisions to stop using their products before failure), based on a self-administered consumer questionnaire survey in Japan. We also compared the influential obsolescence reasons between different product types, namely up-to-date products (products are often updated due to the changes in their looks or technology) and workhorse products (products of which functional utility is valued). The results indicated that failure was the dominant obsolescence reason for PCs and microwaves. However, for microwaves, the representative workhorse products, obsolescence due to relative obsolescence was more likely to shorten the lifetime than that due to failure. Furthermore, relative obsolescence, most notably functional obsolescence, was found to be as influential as failure for all years of use in the case of digital cameras, which are representative up-to-date products, indicating that the process of product obsolescence differs depending on the product type. The second study analyzed the relationship between obsolescence reasons and household characteristics, including household income and residence type. Datasets from a Japanese official statistics survey on five types of EEE were utilized. We found that functional obsolescence was more prevalent among higher-income households, especially for mobile phones, which also represent up-to-date products. In addition, households living in rent house or headed by persons aged under 50 years old were very likely to stop using refrigerators, air conditioners, or vacuum cleaners after moving out of the house, and the lifetime of those devices was significantly shorter than that of devices replaced due to other obsolescence reasons. Based on these results, effective measures to prevent product obsolescence are discussed by obsolescence reason and product type.

Sustainable land transition through area neutrality in municipalities

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:14: Transitions (short presentations) (B0.41 KOG)

Natchiyar Balasubramanian [1], ***Aleksander Storebø Bachke*** [1], ***Emma Tagseth*** [1], ***Ottar Michelsen*** [1]

1. *Norwegian Univ. of Science and Technology*

Globally, urban areas and especially cities are expected to triple in size by 2030. Urbanization is a major contributor to global land conversion and contributes to the global challenge of competition for land. The increased population and need for space lead to expansion into surrounding natural and agricultural areas, often neglecting the impacts on land and ecological systems leading to a reduction in the delivery capacity of ecosystems.
Although urbanization causes habitat degradation, increases invasive species, and inhibits ecosystem functions, it can also positively contribute to biodiversity. Urban areas can serve as refugia for plants and animals as well as support the landscape structure through positive and efficient land management strategies. The trade-offs and success are usually dependent on the governing bodies, area developers, and city inhabitants. Governing bodies such as municipalities also play a crucial role in implementing and operationalizing national and international policies related to biodiversity due to their role in area planning. In Norway, municipalities can be capable of designing sustainable landscapes as the major land planning authority and recently several municipalities have pledged to become area neutral. The main purpose of this framework is for municipalities to reduce their negative impacts on nature and achieve zero net loss. Municipalities around are putting forth their land management plans to achieve these commitments.
The municipality of Trondheim is one of the municipalities in Norway to have pledged area neutrality. Trondheim is one of the cities with a growing population and is expected to grow by 28% by 2050 up to approximately 250 000 inhabitants. This makes it a relevant city for a case study as the results can be applied in other growing cities around the world. The municipality has announced an area plan that aims to aid in achieving area neutrality through effective nature management, land use planning, and sustainable urban development.
In our study, we focus on the main stakeholders affected by the area plan, the inhabitants of Trondheim, area planners in the municipality, and area developers. We evaluate the perception of the inhabitants on the new area plan and biodiversity loss. This plan is expected to add pressure on municipality and area planners to avoid negative impacts on natural landscapes from construction and expansion. We are conducting interviews with these stakeholders, i) To understand their perceptions of area neutrality and biodiversity loss, ii) To understand the level of contribution towards net zero action plans, and iii) To what degree the operationalization of the term 'area neutrality' is useful also for reducing the loss of biodiversity. Additionally, we explore the interdependencies of local businesses and municipality regulations to provide better measures and policy recommendations, e.g. to what degree the suggested measures and incentives are able to capture the impact on biodiversity on a scale smaller than overall area planning. Finally, this study provides a holistic evaluation of the existing area plan and will contribute towards expanding the policy to make this ambitious area neutrality target achievable.
Key words: Area neutrality, municipality, biodiversity, Trondheim, land-use

APPLICATION OF TRANSITION LCA METHOD ON CO2 CAPTURE AND UTILIZATION IN A CEMENT PLANT

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Eva Quéheille [1]***, Anne Ventura*** [1]***, Lauredan Le Guen*** [1]***, Eric Lefebvre*** [2]***, Laury Barnes-Davin*** [2]

***1.** Université Gustave-Eiffel,* ***2.** Vicat*

As a producer of one of the highest emitting construction products (cement accounts for 6% of worldwide emissions), the cement sector is expected to reduce its environmental impacts in order to mitigate climate change. Actions have already led to some improvements, including reducing the proportion of clinker in cement, which is responsible for the majority of CO_2 emissions in the process, due to decarbonation during calcination. But more effort is still required. Of all the options listed by specialized agencies, associations and think tanks, the use of carbon capture, utilization and storage (CCUS) reveals to be a commonly identified solution. CO_2 storage needs to be close or connected (by rail or by boats) to a CO_2 storage site (i.e. aquifers or depleted reservoirs). However, these storage sites are few and, in most cases, CO_2 utilization is the only solution.
The Vicat group, an international cement manufacturer, is therefore exploring CCU solutions as one of the most effective ways to complete its roadmap towards neutrality on its value chain by 2050. Vicat is involved in projects aiming to produce methanol by the combination of CO_2, captured from a cement plant, and H_2, produced by water electrolysis. Methanol market will be transport or chemical industries. The objective is twofold: to valorize CO_2 from the cement plant and to provide a methanol with less impact than current conventional production from fossil fuels.
To confirm the environmental performance of these projects, technological choices have to be carefully made as some research articles pointed out the importance of the production mix of electricity used for water electrolysis. Other points of attention are the technology for water electrolysis and CO_2 capture, opportunities to recycle the heat of the plant in the process, which use for the methanol... Other topics are also to investigate, such as the competitiveness of the produced methanol within the territorial context in which the cement plant is located. The methanol could not be environmentally viable if it cannot enter the local markets; it will simply be stored, which will lead to increased environmental impacts for the production of an unused product.
To assess this project as thoroughly as possible, a Transition Life Cycle Assessment (LCA) is conducted. This recent LCA method (doi: 10.3389/frsus.2022.801668) aims to evaluate transition solutions by associating LCA with Material Flow Analysis (MFA) and economic models in a prospective and territorial context. The on-going application of Transition LCA on Vicat group's CCU projects should lead to several results. 1) Identify the technological and energy scenarios which should provide the most interesting environmental performances; 2) Estimate the conditions for the methanol to enter the territorial markets; 3) Bring insight on the effects of the project on the local actors and their potential action levers; 4) Be an example for the application of the Transition LCA methodology, and perhaps a source for improvement.
The poster focuses on the presentation of the on-going Transition LCA study (i.e. Vicat's CCU projects) by describing the context, the methodology and the expected results.

Middle-out evolution of greenfield eco-industrial parks: The case of GreenLab Skive, Denmark

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

***Lucia Mortensen* [1], *Lone Kørnøv* [1], *Leonie Schlüter* [1], *Allan Næs Gjerding* [1]**

***1.** Aalborg University*

Transforming into eco-industrial parks (EIPs) by applying collaborative measures and stakeholder involvement is a practical and political answer to the decline of existing industrial parks (Morales & Diemer, 2019; Simboli, Taddeo & Morgante, 2014). This has received ongoing attention both in literature and practice (Dai et al., 2022) as a brownfield approach, where EIPs develop through retrofits and new strategies of existing establishments. Less attention has been paid to the contrasting approach: that of greenfield development where sustainability is inherent in the planning, design, and construction phases of the ensuing establishment. The few existing studies evolve around a top-down approach, where planning is implemented with governmental financial support and driven by national governmental programs or research institutions (Behera et al., 2012; Sakr et al., 2011).

The present study shows the potency of a middle-out approach (Costa & Ferrão, 2010) to greenfield EIP development driven by multi-stakeholder processes engaging a large group of actors, such as companies, research institutions, public bodies, public and private funding, and the community at large. It devotes itself to exploring the emergence paths of a greenfield EIP by analyzing the evolution of GreenLab Skive, a Danish eco-industrial park.

GreenLab Skive is the world's first EIP with Power-to-X integrated into an industrial symbiosis network and positions itself not only as an EIP, but also as a technology enabler and a national research facility, specialized in accelerating research and technology to scale (Sorrenti et al., 2023). It is located far from major urban centers, and its emergence initiated more than a decade ago (Alashpekova & Kørnøv, 2018).

Methodologically, the study draws on an analytical framework developed from a variety of process models for developing EIPs (among them Mortensen & Kørnøv, 2019). The focus is on the evolutionary path, including emergence and implementation phases, actors involved, and the joint creation of the journey through staging narratives. Special attention in our research is given to how research communities serve as key player in the facilitation of EIP development. A triangulation of data collection methods is used including historical and real-life data collection methods, such as individual and focus group interviews, observations, and document analysis. The study monitors GreenLab Skive in real life for a 6-months period.

The results contribute to theory by providing a new way of mapping EIP development. The study also has implications for practice by providing actionable insights and applicable guidelines for EIP design, development, and implementation. Both the theoretical and practical contributions add value to our knowledge on how to facilitate EIP development.

Systematically Assessing Environmental Impacts of Pharmaceuticals - Lessons Learned

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Tuesday, 4th July - 12:14: Impacts (short presentations) (B0.16 KOG)

Lowik Pieters [1], ***Martijn van Bodegraven*** [1], ***Rosalie van Zelm*** [2]

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Over the life cycle of healthcare processes and products, many emissions and resource extractions occur that can have negative health and environmental effects. If one person is cured today, at the expense of making other people sick tomorrow, healthcare becomes counter-productive. Safe and sustainable pharmaceuticals can contribute to a healthy healthcare system. To understand the environmental consequences of pharmaceuticals, Life Cycle Assessments (LCAs) can provide valuable input. However, it is unclear to what extent pharmaceutical LCAs are representative, reliable and accurate for impact assessment in the healthcare sector.
Therefore, with a literature review on pharmaceutical product LCAs, we aim to present how challenges in performing and interpreting pharmaceutical LCAs can be addressed in the future. Moreover, the review serves to further advance the research field and to come to applicable recommendations for a sustainable healthcare sector.
The work includes 62 LCA studies of pharmaceutical products retrieved through a systematic literature search on Scopus. The studies were analyzed based on the four phases of LCA as described in ISO14040 and 14044 standards: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; 4) interpretation.
Preliminary results showed that key challenges identified in LCAs for pharmaceutical products are:

1. Variations in methodological choices and high case specificity, limiting usability of pharmaceutical LCAs for purposes beyond their stated goal and scope;
2. Limited transparency of the life cycle inventory, hampering our understanding of sources of variability in pharmaceutical LCAs and reproducibility;
3. Impact assessment tends to be limited to Climate Change, whereas impact models on pharmaceutical-specific impacts of toxicity, such as endocrine disruption and antibiotic resistance, are not evaluated.
4. Consistency, completeness and representativeness are difficult to interpret due to missing sensitivity, consistency and completeness analyses.

During the presentation, solutions to address these challenges will be presented.

Prospective life cycle assessment (pLCA) of emerging carbon capture technologies used in the steel industry

Sunday, 2nd July - 13:00: Poster session 1 (Pieterskerk)

Thomas Hennequin [1]***, Rosalie van Zelm*** [2]***, Mark A.J. Huijbregts*** [1]

1. Radboud University Nijmegen, Department of Environmental Science, 2. Department of Environmental Science, Faculty of Science, Radboud University, Nijmegen 6525AJ

Iron and steel are necessary commodities in ever-growing demand. The associated industry is responsible for a significant fraction of global anthropogenic greenhouse gas emissions, which needs to be minimized. One solution to mitigate this impact is the use of carbon capture and storage (CCS) technologies. Two such technologies are currently being developed within the EU H2020 project C4U: (i) CASOH, a calcium-assisted steel mill off-gas hydrogen production system, and (ii) DISPLACE, a high-temperature sorption-displacement process for CO_2 recovery. The goal of this study is to assess the mitigation potential of these two emerging CCS solutions and guide their development from an environmental standpoint.

To assess the potential environmental impacts and benefits of these solutions systematically, the life cycle assessment (LCA) approach can be used. Specifically, because the technologies only currently exist at a low technology readiness level (TRL), we used prospective LCA to predict the impacts and benefits of the two CCS technologies at a higher TRL. Life cycle inventory (LCI) data were gathered from technology developers. We applied the same methodology to upscale both life-cycle inventories from the pilot to the industrial scales. We collected expert input to build high TRL life cycle inventories. We conducted contribution analyses to identify the main drivers of their footprint and scenario analyses to investigate different potential development paths, such as different sources of heat. Moreover, options for the transportation of CO_2 were modeled using scenario analyses.

Preliminary results indicated that the main driver of the environmental footprint of the two emerging CCS solutions is energy consumption across the impact categories examined. In the presentation, results will be shown on current and future TRL environmental performance for both capture solutions. Potential industrial synergies will also be investigated. Using our results, the mitigation potential of the different CCS technologies can be fairly quantified, and recommendations for their development provided. Finally, similarities and differences between the implementation of the methodologies used to upscale the inventories will be discussed to help further develop the pLCA framework. We notably found that in complex systems, the input of experts based on technology simulations was invaluable.

Poster Session 2

Enhancing household water consumption prediction by the water-energy nexus concept: a case of Beijing, China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wednesday, 5th July - 11:00: Water 2 (B0.16 KOG)

***Zonghan Li** [1], Yi Liu [1], Chunyan Wang [1]*

***1.** Tsinghua University*

The rapid increase in residential water use is attracting attention. Due to rapidly growing urban settlements, household water consumption is expected to increase significantly by 2050. The challenges posed by the surge could be better addressed by predicting future water consumption. However, the estimation of residential water demand remains one of the most challenging problems in cities to date.

This study aims to enhance household water consumption predictions using the water-energy nexus concept, i.e., considering energy use (EU) features and electricity consumption (EC) features in the model, to better understand the household water-energy nexus. We designed a stepwise-like approach that can compare the predictions before and after considering EU and EC, utilize household-level data and establish four annual water consumption prediction models with the stepwise-like approach. The four models were applied to data from 1320 surveyed households in Haidian and Tongzhou Districts in Beijing, China, in 2020 by employing a traditional statistical technique, OLS, and machine learning techniques, including random forest (RF) and extreme gradient boost (XGBoost).

The results illustrate the importance of the water-energy nexus in enhancing the goodness of fit and accuracy of household water predictions: models adding EU&EC and EU had lower root mean square errors (RMSEs, 9.0% and 5.4% on average, respectively), lower mean average percentage errors (MAPEs, 8.8% and 5.5%) and higher coefficients of determination (R2, 30.4% and 20.2%) than the basic model; the total importance of EU was 3.8% higher than that of water use features. The role of machine learning techniques in the predictions was also revealed, as XGBoost performed the best among the three techniques. Compared with other predictions with similar spatial scales, nature of data and sample size, the R2 of this study was also improved by at least 23.8%.

In short, the water-energy nexus concept not only enhanced the performance of household water consumption predictions in this study compared with previous works, but also provides novel and efficient improvement approaches for future related studies. The enhancements can help us reach a better understanding of the household water-energy nexus and facilitate better infrastructure planning and management in cities.

Absolute Environmental Sustainability Assessment of Chemical Products – transgression level of nature's carrying capacity and potential for nature-based solutions

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ying Xue [1], ***Bhavik Bakshi*** [1]

1. *The Ohio State University*

The chemicals sector is the third largest industry subsector in terms of direct CO2 emissions, with more than 900 Mt produced annually. The chemical industry will play a major role in global transition to "Net-zero by 2050" which is driving research efforts aimed at decarbonizing the life cycle of products, conducting sustainability assessments of current processes and products, identifying hotspots, and redesigning supply chains. This study focuses on carbon and conducts a critical absolute environmental sustainability assessment (AESA) of four major chemical products: ammonia, methanol, ethylene, benzene. Current AES metrics for chemicals are highly aggregated at a global scale with subjective downscaling approaches which are not robust. This study utilizes the techno-ecological synergy (TES) framework, which incorporates the role of nature into life cycle assessments (LCA) by using biophysical models at multiple spatial scales while considering the responsibilities of stakeholders from individuals to countries. Scenarios for future improvements were studied for each producer. Results show current levels of transgression and identify possible actions that stakeholders can take to achieve "Net-zero". They also show the benefits of our multiscale approach compared to the approach based on planetary boundaries.

Sustainability assessment methods such as LCA are useful for comparing the environmental impacts of alternatives in terms of their relative sustainability. AES has been proposed to improve upon relative sustainability by identifying absolute reference values and be compared with environmental impacts directly. The planetary boundary (PB) framework is one of the widely used AESA methods. It quantifies thresholds for several earth system processes and identifies the safe operating space (SOS) for human development. PB-based AESA downscales SOSs from a large scale (global or subglobal) to process/product level according to certain sharing principles. This method provides holistic perspectives, but it ignores the spatial heterogeneity and introduces subjectiveness. To overcome these shortcomings, we use the multiscale TES method which integrates local and regional information with PB. TES quantifies ESs through biophysical models from different spatial scales and uses them as ecological thresholds which brings in high geospatial resolution and reduces subjectiveness. Biophysical models enable exploration of nature-based solutions by quantifying the ESs from available area for ecosystem restoration then integrated into assessment or design.

In this work, we assess the top five producing countries for ammonia, methanol, ethylene, benzene. The environmental impacts for these chemicals are assessed through cradle-to-gate process-based LCA. Carbon sequestration capacity per year for each stakeholder was calculated based on carbon sequestered within the country and an allocated amount from the publicly owned capacity at the global scale (oceans). For more comprehensive analysis, different sharing principles were applied: emission, GDP, GVA, historical emission. We calculated the AES transgression level for each product in each country and also calculated an aggregated value at the global level. The results highlight the spatial hotspots for the current chemical industry. By quantifying 'future' carbon sequestration from available land area for ecosystem restoration, reforestation in this case, in each country, we identify improvements on transgression level using nature-based solutions. For further investigation into achieving "Net-zero" chemical production, this study also compares scenarios for different energy sources by disaggregating energy inputs from the LCA network of each chemical and replace them with electricity from solar, wind, nuclear, mixed, etc. Different carbon capture and storage techniques like membrane-based processes are also studied.

Life-cycle assessment of Li-ion batteries with focus on water risks related to critical metals

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Yan Du [1]***, Ranran Wang*** [2]***, Julie Zimmerman*** [3]

1. Chemical and Environmental Engineering, Yale University, 2. Institute of Environmental Sciences (CML) - Universiteit Leiden, 3. Yale University

As one revolutionary product of renewable energy technology, electric vehicles (EVs) based on Li-ion batteries (LIB) has grown rapidly worldwide over the past decades. Although known as a cleaner alternative to vehicles relying on conventional fossil fuels, EVs raise concerns about their current and long-term environmental impacts and resource risks. Existing research focus on technical upgrades of LIBs for EVs and their potential impacts on global warming and biodiversity degradation, while global and regional water quantity and quality risks associated with metals required for batteries, including lithium, cobalt and nickel, gain insufficient attention. Considering metals as a critical part of the water-energy nexus related to LIBs, our study first evaluates the water-use efficiency along the supply chain of metals for LIBs production, especially during mining and refinement stages. Local water scarcity levels based on water basins of the largest mines in Congo, China, Indonesia, and Philippines are integrated into the analysis as weights, which are subsequentially used for the setup of water-use input-output systems. Then, we analyze the life cycle environmental impacts of three major types of LIBs - $LiMn_2O$ (LMO), $LiNi_xCo_yAl_{1-x-y}O_2$ (NCA), and $LiNi_xMn_yCo_{1-x-y}O_2$ (NMC) batteries - through an integrated hybrid life-cycle assessment (LCA) approach. The life cycle inventories of LIBs contain raw materials and component manufacturing, battery assembly, use phase, disposal and recycling, as well as other relevant background processes. Both midpoint and end point environmental impact indicators are thoroughly evaluated. With zero-waste future being an increasingly attractive common goal, we also construct various waste battery recycling and metal recovery scenarios to assess their impacts on required resources, especially metals and water. Moreover, we perform sensitivity analyses on the current and emerging cathodes with different chemical compositions, as there has been an ongoing shift towards high nickel content. Our preliminary results imply that battery cell production exacerbates the regional water stress levels and negatively impacts the local community through the shortage of water allocated to other productive sectors. Besides, the modes of EVs consumer use, including driving distances and local climate, along with the end-of-use stage of LIBs in EVs, reveals the most significant differences among the three types of LIBs in this study. Further interpretation of the results is expected. With detailed information, the results of this study will greatly contribute to the understanding of the water risks posed by the life cycle of LIBs, which may become a limiting factor to the supply of metals required for their production, and will provide valuable insights into the improvement on water-use efficiency of metal-producing countries, technical advancement of LIBs, and policy on the future production and use of EVs with several widely favored types of LIBs.

Methodological Comparison of Prospective LCAs and EE-MRIO for Modelling Circular Economy Measures: A Case Study on Smartphones in Germany

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Malte Besler [1], ***Antonia Loibl*** [1]

1. Fraunhofer Institute for System and Innovation Research ISI

In light of environmental degradation and the transgression of planetary boundaries, the concept of circular economy (CE) is discussed as a vision for more sustainable systems of production and consumption that reduces resource use, waste, and related environmental impacts. Evaluating possible pathways for and the impacts of the transition from a linear to a circular economy is crucial to enable informed decisions about the design, implementation, and monitoring of circular economy policies and to identify opportunities for improvement. This requires comprehensive modelling approaches that can account for complex interactions between the economy and the environment. Two tools that are suitable for this purpose are (prospective) life cycle assessments (LCAs) and environmentally extended multi-regional input-output (EE-MRIO) models. While LCAs provide detailed bottom-up information on the environmental impact of products and related processes, EE-MRIO models give a top-down view of interactions between economies and sectors and their respective environmental impacts. Both methods offer distinctive perspectives for CE modelling, which are broadened by their different resolution, units of measurement, and data basis.

This study aims to provide insights into the advantages, limitations as well as compatibility of the two methodological approaches through a systematic comparison of results. Impacts of CE measures are therefore modelled with prospective LCA as well as the EE-MRIO model EXIOBASE 3 using smartphone consumption in Germany as an illustrative example. The German smartphone demand is projected until 2040, using prospective trajectories based on historical demand and data from the IPCC AR6 scenario database to set a perimeter for CE modelling. Three CE measures are analyzed: Product lifetime expansion, design improvements and increased end of life recycling. The prospective LCA and the EE-MRIO model are adjusted to the scenario context and the impacts of the CE measures on resource use and GHG emissions are modelled using both methods. The respective results on the environmental impacts are analyzed to assess the scope of variance due to the choice of methods and their applicability to enable informed decision making in the case of smartphones.

The findings emphasize the importance of selecting appropriate methods based on the research question through considering their strengths and limitations. An integration of methods can provide a thorough and robust assessment of the environmental impacts of CE measures and counteract potential biases due to choice of methods.

Global trading impact on Biodiversity loss in Africa

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ludi Liu [1], ***Tay Seyram Nana Addo*** [1], ***Xin Tian*** [1]

1. *Beijing Normal University*

Biodiversity lose is one of the global environmental crises facing the mankind in this century. Africa is one of the regions with the highest biodiversity loss globally. With globalization and international trade, Africa's biodiversity is increasingly affected by impacts from other regions and faces growing challenges. We use the Multi-Regional Input-Output model to estimate the biodiversity lose in Africa from 2000 to 2018, and identify the main countries that cause the biodiversity lose by international trade. The results showed that the biodiversity lose in Africa accounted for 9.7% of the global biodiversity lose in 2018. The biodiversity lose was most significant in Madagascar and South Africa, accounting for 63% of the total lose in Africa in 2018. The international trade was responsible for 26% of the biodiversity in Africa in 2000 and 17% in 2018. From the international trade perspective, the consumption in the West Europe and Asia & Pacific was the most important driver for the biodiversity lose in Africa, with increasing trend in Asia & Pacific and decreasing trend in West Europe. In the West Europe, France, Germany, Italy, and the UK have the most significant influence on the biodiversity lose in Africa, and most of the lose concentrated in South Africa and Madagascar. In Asia & Pacific, India, China, and Japan were most responsible for the biodiversity lose in Africa, especially in South Africa, Tanzania, and Madagascar. Our results can help to identify the important international trade path transferring the biodiversity pressure to Africa and to allocate the responsibility of biodiversity lose in Africa, especially for the developed countries whose consumption caused the biodiversity loss in Africa.

The Design of Transportation Pipelines for Carbon Capture and Storage in Taiwan with GIS

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Chien-Ching Chang [1], *Yu-Nien Ku* [1], *Qi-Xian Wu* [1], *Tzu-Yang Chiang* [1], *Pei-Te Chiueh* [1]

1. National Taiwan University

Carbon capture and storage (CCS) is a promising technique to reduce the impact of climate change by capturing carbon dioxide from various sources and storing it instead of releasing it into the atmosphere. This method has the potential to mitigate the effect of greenhouse gases on the environment and climate.

This study aims to provide an overview of the use of Geographic Information System (GIS) in the design of transportation pipelines for CCS in Taiwan. We analyzed CO_2 emission sources, transportation pathways, and potential storage locations using ArcGIS Desktop 10.8 software.

To identify high-density CO_2 emission clusters and hotspots, this study uses the Kernel Density function within the GIS software, which requires CO_2 emission source data as input. According to the results, the central region of Taiwan is the hotspot of CO_2 emissions, with the thermal power plants being the largest source of CO_2 emissions, including Taichung Power Plant (36,336,000 tCO_2/year), Mailiao Power Plant (25,304,000 $tCO_{2)}$, and Hsinta Power Plant (18,245,000 tCO_2).

Deep saline aquifers, sedimentary basins, and depleted oil fields are considered the most promising sites for CO_2 storage due to their favorable geological characteristics. In Taiwan, the deep saline aquifer is widespread in the western region, but its vast distribution limits its usefulness as a CO_2 storage site indicator. Furthermore, historical records show that most earthquakes occur in the eastern region of Taiwan. Therefore, the first choice for CO_2 storage sites in Taiwan is the sedimentary basin and depleted oil fields located in the west. These sites, which are distributed from north to south in the western region, possess suitable geological characteristics to support CO_2 storage. Despite this, additional scientific evidence is required to ensure the safety and effectiveness of CO_2 storage in these sites, including an analysis of the geological features and processes that support CO_2 storage, as well as potential seismic risks.

The study also uses the Cost Path function within a GIS software to perform spatial source-sink matching for CCS and assess potential carbon routes for future implementation, such as a pipeline network. For this study, we selected industries (point sources) with annual CO_2 emissions exceeding 100,000 t as the sources, and the centroids of the sedimentary basin and oil field as the sinks. Using cost path analysis, we then determined the recommended pipeline network for carbon capture and storage (CCS) between the sources and sinks.

The detailed case study in Taiwan demonstrates that GIS is a valuable tool for assessing the feasibility of CO_2 capture, transportation, and storage. However, conducting a comprehensive feasibility assessment of CCS in other regions requires further investigation. This includes analyzing the geological features, assessing the physical properties of the pipeline, evaluating the effectiveness of CO_2 capture technology, determining the capacity of CO_2 storage sites, and assessing the actual volume of CO_2 emissions from the source. If all of the investigations mentioned above are completed, GIS is an optimal way to design the pipeline network for CCS.

Prospective Life Cycle Inventories for Rapid Innovation Technologies: A hotspot scenario analysis for global integrated circuit manufacturing

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Rylie Pelton [1], ***Tim Smith*** [2], ***Yi Yang*** [2], ***Jessica Blascak*** [1], ***Joe Pelton*** [1]

1. LEIF, 2. TASA Analytics

The information and communications technology (ICT) sector contributes around 2-4% of global greenhouse gas emissions. Many companies across the ICT industry, including Microsoft, Amazon, Google, Apple, BT and Sky are responding by setting commitments and reduction targets addressing operational energy use, estimated to produce anywhere from 10-70% of the total life cycle emissions, and embedded emissions from manufacturing, estimated to contribute around 30-90% of emissions from the sector (Frietag et al 2021; Kline 2019; Teehan and Kandlikar 2013). Recent analyses have identified integrated circuit semiconductors as being the primary contributor to embedded manufacturing impacts of data centers and computing systems (Kline 2019; Jones et al 2013; Yao et al 2010). Parameterized LCA can be further used to examine differences across technology and design options within a given product type, across geographic production locations, and across material and energy sourcing decisions (Pelton and Smith 2015; Murphy et al 2003). Such approaches are especially useful for highly evolving products and industries, such as in the integrated circuits industry, where life cycle assessment information quickly becomes outdated from the rapid changes in production processes accompanying each product generation's technological improvements (Murphy et al 2003; Kline 2019). Material and other design parameters are also often kept as trade secrets and consist of hundreds of steps that complicate and limit construction of life cycle inventories (Derbyshire 2016; Garcia Bardon 2020). Indeed, few LCAs of semiconductors have been conducted and those that have were conducted or based on data from over a decade ago (Schmidt 2012; Boyd 2012; Murphy 2003; Krishnan et al 2008; Villard et al 2015; Liu et al 2010) or are not peer reviewed (Kline 2019; Garcia Bardon et al 2020). Further, semiconductor datasets in LCA databases (e.g., Sphera GaBi thinkstep, ecoinvent) often rely on these dated inventories, where for example semiconductor datasets across node generations in Sphera are based on underlying data sources ranging from 1995 to 2011, and the aggregated process nature of the datasets prevents further parameterized modification. These aspects limit their use in assessing potential mitigation opportunities, through for example, differences in processing technologies, design features, or geographical differences.

Hotspot scenario analysis is a type of parameterized LCA approach (HSA-LCA) that focuses detailed parameterized inventory efforts on the stages and inputs that contribute greatest to overall life cycle impacts, combining detailed scenario results with average product or industry impact estimates for less impactful components of the product life cycle. These approaches increase comparability of system boundaries and assumptions, providing directional information on the relative environmental preferability of various product design and production contexts without the significant costs of conducting full LCAs on each product and product iteration (Pelton and Smith 2015; Pelton et al 2016). Given the contribution of integrated circuit semiconductors to data center emissions, and the substantial portion of semiconductor emissions generated from operational scope 1 and 2 sources, better understanding integrated circuit semiconductor emissions and the levers for reducing emissions is a critical next step towards reducing ICT GHG emissions and achieving corporate commitments. Here, we demonstrate this approach by developing a parametric model to delineate semiconductor emission factors between different product types, regions, wafer sizes, processing technology types, product generations, abatement options, and other design specifications, helping pave the way for rapid assessment of upstream ICT emissions and mitigation opportunities for meeting GHG reduction targets.

Exploring the Economics of Urban Water: Valuation, Recycling, and Sustainability

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wednesday, 5th July - 11:30: Water 2 (B0.16 KOG)

Carlos López-Morales [1]

1. El Colegio de México

Global trends on population, urbanization, and localization of economic activities suggest that the global economy increasingly becomes urbanized, both in so-called developed and developing countries. A highlight of this process is that the dynamic interactions among metropolitan zones, medium cities, small cities, and rural locations are becoming increasingly complex and intertwined. One of the most outstanding features of this complexity, and one receiving small attention so far in disciplinary literatures, has to do with the way in which these economic entities appropriate water as an essential material input. In other words, the degree to which hydrologic cycles are intervened is dependent on the urbanization process occurring in local watersheds. This paper explores the conceptual and theoretical understanding of the economics of water as an essential economic and ecological input for both social activity and ecological sustainability in the context of the urbanization process. The premise of this exercise is that economic models at different scales (national, regional, or local) should be capable of capturing the fundamentals of water's appropriation at different degrees or urbanization, so as to be able to assess alternative solutions to unsustainable situations. This paper develops a conceptual model of an urban economy embedded in a highly urbanized water basin with the aim of exploring the interdependencies among hydrologic sustainability, competing economic uses, and the generation, treatment and reuse of wastewater under alternative scenarios of water availability. The findings highlight the important roles of treatment technologies, water infrastructure, and administrative arrangements as the foundation for a functioning governance adequate for water sustainability

Could Norway supply its own fertilizer? A high-resolution analysis of the agricultural phosphorus cycle.

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Phosphorus (P) is essential for food production from plant and animal origins. Modern agriculture techniques rely on adding mineral P to maintain productivity, resulting in a largely linear use of resources. However, the availability of mineral P resources is limited and highly concentrated in a few regions, which can lead to resource scarcity and economic barriers that restrict its accessibility. The release of nutrients from agricultural soils into surface waters through erosion and runoff increases the risk of eutrophication. Previous studies of the P cycle in Norwegian agriculture show a very low efficiency: crop-producing areas rely on mineral P imports while livestock-dense areas generate a nutrient surplus through manure that accumulates in the soil. Designing effective strategies to close the P cycle requires addressing the differences in farm types causing this regional disparity.

Here, we present a spatially explicit multi-scale material flow analysis (MFA) model of the Norwegian P cycle at the farm level for the period 2017 to 2019. P cycles were developed for approximately 40,000 farms, differentiating between 20 crop and 18 animal species. The model was calibrated using statistics from the Norwegian Agriculture Agency, Statistics Norway, data from literature, and information from expert interviews. The MFA model was used to identify the areas with a P surplus from manure and the areas with a P deficit that is covered by mineral fertilizers. A set of scenarios was modeled to analyze the potential for substituting mineral P fertilizers with animal manure at different scales through processing and trade.

The results show the differences in phosphorus use efficiency at different production stages across farms with different crop and livestock compositions. The national aggregation shows an accumulation of 11 kt of P in the cropland. The highest P accumulation was found in the municipalities of the west coast, areas with the highest animal density. High accumulation also occurs in the vicinity of large urban areas, due to their more intensive use of sewage sludge, which has a lower plant availability of P than mineral fertilizers or manure. Optimizing manure fertilization in manure-producing farms could reduce the national mineral P imports by up to 50%. Trading the remainder of surplus manure between farms across municipalities, counties, and nationally could increase the reduction to 90%.

Secondary fertilizers tend to be rich in P but poor in N and K. Strategies for more efficient use of manure need to be informed by fertilization plans tailored to individual N, P, and K nutrient needs. Optimized manure application may also require improvements in storage and application infrastructure. If Norwegian agriculture is to effectively reduce its dependence on mineral P imports, systems must be put in place to facilitate nationwide infrastructures for the collection of secondary resources, processing to high-quality fertilizers, and their trade and transport to farmers within and outside Norway.

The Belt and Road Initiative countries play an increasingly important role in global value chains with high carbon emission costs

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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The Belt and Road Initiative (BRI) countries, with developing countries as the main body, are taking more responsibility for carbon emission reduction while obtaining economic benefits in Global Value Chains (GVCs). However, compared with the increasingly active international trade activities, the impact of GVCs participation of the BRI countries on carbon emission is still poorly understood. Using a multi-regional input-output model, we trace the value added and carbon emissions of 65 BRI countries participating in GVCs five years before and after the initiative was proposed in 2013 in a consistent flamework. The results show that BRI countries are the pivotal contributors to global carbon emissions, and they only get less than 40% of the global value added benefits at more than 60% of the carbon emission in participating in GVCs activities. About 40% of the carbon emissions and value added of BRI countries in GVCs come from the trade activities between them, and this proportion is gradually increasing, indicating that BRI countries are becoming an internally active economy group. The flow pattern of carbon emissions and value added within BRI countries has changed from unilateral to multilateral, but long tail effect is found in the trade among BRI countries, that is less than a quarter of countries contributed more than 80% of carbon emissions and value added of BRI countries. Meanwhile, the growth momentum of carbon emissions has been curbed, while the growth of value added has been steady among the trade between key nodes of BRI countries after 2013. As for production carbon efficiency, the overall carbon emission intensity of BRI countries declined, but 56.9% of BRI countries saw an increase in their carbon emission intensity in GVCs after 2013, indicating that the growth momentum of carbon emissions was curbed because the emission intensity of major emitters decreased, which concealed the hidden danger of rising carbon emissions of other BRI countries in GVCs. The carbon emission intensity in GVCs of BRI countries is positively correlated with their medium- and low- R&D density industry GVC positions, shows that the movement of GVC position upstream can explain the increase of carbon intensity in some countries. Our findings underscore that building the green BRI requires not only the efforts of major emitters to reduce emission, but also the attention of emerging countries to efficiency in the process of GVC participation, especially those countries embedded in GVCs with intermediate goods provision in medium- and low- R&D density industries.

The impact of energy transition policies on land use changes affects regional ecosystem services

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hungxin Chen [1], ***Pei-Te Chiueh*** [1]
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With the progress of time, unlimited exploitation of resources by humans has led to the loss of natural capital, and the value of ecosystem services has gradually gained attention. In recent years, many scholars have put forward the functions of ecosystem services and explained them as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life." For this reason, the preservation of ecosystem services becomes a priority.

In Taiwan, the government aims to achieve a target of 20 GW for solar power promotion by 2025, and ground-mounted photovoltaics will be used in conjunction with aquaculture as the main source of electricity generation. However, converting agricultural land to fishery and electricity symbiosis might lead to major issues in ecosystem services. For example, converting agricultural land into fishery and electricity symbiosis may alter ecosystem services such as Carbon Storage and Sequestration, Sediment Delivery ...etc.

Nowadays, Taiwan's environmental review mechanism only considers sensitive site maps for screening and does not compare the pre- and post-development from the perspective of ecosystem services. Also, Conventional ground management methods used in solar facilities often involve establishing and maintaining low-growing turfgrass. Compared to traditional turfgrass methods, native grassland vegetation can enhance various ecosystem services. Moreover, native grasses and forbs typically have deeper root systems than row crop agriculture and turfgrass.

For this reason, this study aims to explore the changes in ecosystem services in Tainan Cigu and Jiangjun Districts after the conversion to photovoltaic power plant, from different temporal and spatial perspectives. The study focuses on the four functions of ecosystem services: Carbon Storage and Sequestration, Sediment Delivery Ratio, Crop Pollination and Food production. Furthermore, in this study will examine the implications of future solar energy development in the region on ecosystem services.

In conclusion, this study uses the perspective of ecosystem services to explore the impact of the conversion from or aquaculture fishery to photovoltaic power plant of ecosystem services. The study aims to provide a scientific basis for decision-making and to help promote sustainable development.

Substitution of joint-production processes in a sustainable future

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Max Koslowski [1]***, Edgar Hertwich*** [2]***, Richard Wood*** [1]

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"Reduce, reuse, recycle" and many more strategies characterise the idea of a circular economy – an idea that has been around for a while amid our sluggish transition to sustainable development [1]. Among the non-renewable resources necessary for providing services to modern industrial and future sustainable societies, metals take a central role. Their degree of circularity is, however, limited [2,3]. Calls for closing metal and other material loops [4] are supported by earlier modelling results, mandating wide-spread implementation of circular economy strategies for metals to achieve climate and other sustainability goals [5,6]. Importantly, secondary metal production routes must complement and gradually replace virgin material-based ones, yet not at the compromise of unforeseen social and environmental consequences.

In a larger modelling effort, our team constructs sustainable development pathways relying on a set of supply and demand-side interventions implemented in the EXIOfutures model developed by Wood [7]. One envisaged component of this is the possibility for resource-constrained substitution of joint-production processes, for instance of future primary and secondary metal production routes. To that end, we have generalised the rectangular-choice-of-technology (RCOT) model by Duchin & Levine [8]. The original RCOT model holds only for single-production systems, i.e. where potential by-products have been removed by reallocation according to some rule. Our generalised RCOT model may be used in isolation or in combination with other models to investigate counterfactual scenarios of multi-output technology substitution.

The crucial advances in our model are: that no assumptions whatsoever are required in terms of by-product reallocation; that the technology alternatives can be constructed straight from empirical observations or otherwise; and that ambiguities resulting from using physical versus monetary input-output data can be avoided. In our contribution, we present the model and a comparison to the original RCOT model; we highlight the limitations posed by production factor mobility, industry and commodity aggregation, and choice of time horizons; and we explain the applicability to underlying physical or monetary supply-use tables for different industry-by-commodity configurations and the thus resulting suitability for modelling circular economy strategies. Lastly, we outline how the model's formalism may be employed, on a more general level, to avoid the reduction from joint to single-production for the use in impact and imputation analyses under the precautionary principle.

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Contribution Analysis: What is it and which questions does it answer?

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Marc van der Meide [1]***, Jeroen Guinée*** [2]***, Reinout Heijungs*** [2]***, Mingming Hu*** [3]***, Bernhard Steubing*** [4]

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Life cycle assessment (LCA) can give important insights into the environmental performance of a product or service, however, with common use of background databases like ecoinvent the amount of produced data points has become very large. This large amount of data can be hard to extract useful information from. An essential methodology to extract useful information from LCA results for LCA practitioners is contribution analysis. Contribution analysis aids LCA practitioners in understanding and communicating their LCA results.
Contribution analysis is always applied to analyze the contribution *from* some entity (e.g. (groups of) processes, (groups of) environmental interventions or life cycle stages) *to* another entity (e.g. an environmental intervention, impact category results or weighted results) and can be used for different purposes. The three most commonly and broadly applied uses are: finding important or interesting results -or 'hotspots'-, finding important entities for input into sensitivity analysis, and finding errors in the used data.
Despite the widespread use of contribution analysis in the LCA field, a complete definition of contribution analysis is lacking, which leads to many different implementations. While good examples of contribution analysis exist, many LCA studies lack clarity in their methodological choices around contribution analysis or communication of results. This problem makes LCA studies less transparent and harder to replicate, potentially calling the validity of results into question.
We aim to structure different approaches to contribution analysis and the *to/from* role different entities may have with the goal of helping LCA practitioners to make more conscious and transparent choices regarding contribution analysis, better understand their results and finally to better communicate their results.
We introduce common approaches to contribution analysis and how each works in theory. Next, we demonstrate the different approaches using a simplified case study.
The approaches treated are:

- Contribution analysis of individual flows, (groups of) processes and (groups of) environmental interventions
- Contribution analysis of the supply chain (Graph traversal/Sankey/Tree)
- Contribution analysis of life cycle stages (Different stages consisting of (multiple) processes)

These different approaches of contribution analysis are treated and explained in detail and the differences in results from a simplified case study are discussed.
Finally, we compare and discuss the different approaches, (i) what input each approach needs, (ii) how their results differ, and (iii) what questions they may answer and (iv) the advantages and disadvantages of each approach.

Scenario analysis of the environmental impact and economic feasibility of expanding bio-based and bio-degradable PHBH production

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Kota Chida [1]***, Eri Amasawa*** [2]***, Jun Nakatani*** [3]***, Masahiko Hirao*** [2]***, Shunsuke Sato*** [4]

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Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBH) is made from biomass resources and has a characteristic of biodegradability in both soil and seawater. PHBH is produced by feeding a specific microorganism with a carbon source such as vegetable oil, and currently, 5,000 t/y is produced commercially using palm oil as a feedstock [1]. In addition, technology development to produce PHBH from carbon dioxide and hydrogen is currently underway. In order to expand PHBH production, it is necessary to clarify the feasibility of expanding PHBH production.

In this study, scenario analysis of the environmental and economic performance of PHBH production was conducted, where the scenarios explored future expansion of PHBH production. For the production using carbon dioxide and hydrogen as feedstock, the inventory was estimated by designing the process with reference to the current production process using vegetable oil as feedstock. We will present the results of scenario analysis considering the future increase of feedstock, i.e., vegetable oil and hydrogen, development of hydrogen production technology, changes in the power mix, and development of recycling technologies.

[1] E. Amasawa, et al., "Climate Change Implications of Bio-Based and Marine-Biodegradable Plastic: Evidence from Poly(3-hydroxybutyrate-co-3-hydroxyhexanoate)," Environ. Sci. Technol., 55, 3380–3388 (2021)
21)

Evaluating the sustainability potential of Black soldier fly meal for laying hens' feed using LCA

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Daniela Dominguez Aldama [1], ***Nathan Pelletier*** [1]

1. The University of British Columbia

The egg production is the most resource-efficient industry among the livestock sector, however, the production of layer feed remains a key contributor to the overall environmental burdens of the products. Therefore, as the industry continues to grow, so does the demand for low-impact and quality feed. The valorization of low-cost biomass via insect production represents a promising strategy in this context. The Black soldier fly (BSF) is one of the most promising species for animal feed due to its efficiency in converting several biomass types into a high-quality source of protein and fat for animal feed, and because it has a shorter growing cycle compared to other insect species.

The purpose of this study was to use Life cycle assessment (LCA) to evaluate the potential of using Black soldier fly (BSF) meal as a sustainable feed input in the egg industry. Using a commercial producer of BSF as a case study, the goal was to identify the areas with the highest burdens and evaluate opportunities to improve the overall environmental performance of the BSF products. The scope of the study included the production and processing of the larvae, the production of the insect-based feed, and its use to the egg farm. Additionally, to identify the impact reduction potential, different scenarios were evaluated based on varying production scales, alternative technologies and energy sources, as well as alternative substrate diets for larvae rearing. The results showed that producing BSF meal at a large scale could have important environmental benefits and trade-offs compared to the conventional layer feed, depending primarily on the composition of the insect diet and the use of the BSF co-products.

Integrating environmental parameters in energy system modeling

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Alexander de Tomás Pascual [1]***, Francesco Lombardi*** [2]***, Miquel Sierra*** [1]***, Inês Campos*** [3]***, Stefan Pfenninger*** [4]***, Cristina Madrid-López*** [5]

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Environmental parameters are key in the definition of sustainable energy systems, yet excluded from most energy system optimization models. Still, decision-making may be misleading without considering them. Environmental analyses of the energy transition are a key part of industrial ecology but are often performed without any input from the information users.

In this work, we assess the systemic impacts of energy transition pathways in Portugal. Using the Calliope energy modeling framework, 250+ optimized energy system pathways are generated. A Delphi study helps us identify the relevant criteria for the stakeholders as regards the environmental assessment, which is performed with ENBIOS, a python package that integrates Life Cycle Assessment (LCA) with a metabolic analysis based on complex relations.

Furthermore, we aim to analyze each of the 250+ pathways generated to look for the most sustainable configurations from an environmental point of view. To do so, we propose a method to find the pathways with the lowest overall environmental impact. We also aim to include an uncertainty analysis in the Calliope/ENBIOS cascade by building a soft link with Brightway's data distribution capabilities. These study's findings highlight, which kind of energy transition configurations translate into better environmental performance.

Linny-R: Elegant diagram-based modeling and simulation of (smart) clusters, energy grids and markets

Monday, 3rd July - 12:21: Energy (short presentations) (B0.16 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Pieter Bots [1]

1. Delft University of Technology

Climate change, recent geopolitical tensions and the need for a more circular economy force industry, energy systems operators, and market regulators to adapt. This poses strategic decision making challenges that call for simulation models to assess the consequences of large scale variable renewable energy sources (vRES), storage, interconnection, demand response and power-to-X, and to appraise strategies for capacity expansion and other investments at multiple spatial and temporal scales. Enterprises need to evaluate business cases for these investments while negotiating with potential partners as they explore opportunities for industrial symbiosis. Grid operators have to deal with large uncertainties in capacity demand, which makes robust network expansion planning more challenging.

There appears to be no lack of specialized software tools, but rather of policy modeling capabilities. Tools for policy modeling should (1) permit modeling and analysis of synergies across sectors and temporal scales in high resolution, (2) provide open access and transparency, and (3) further engagement and trust between model developers, policy/decision-makers and other stakeholders (Chang et al., 2021; Ryszawska et al., 2021).

The executable graph-based notation Linny-R (https://linny-r.info) fits the need for easy-to-build, easy-to-understand, easy-to-use and easy-to-share models. It permits modeling and simulation of complex unit commitment systems without having to write software code. The graphical notation for networks of processes, products and flows in a cluster hierarchy is concise, yet expressive enough to represent technical aspects (storage, losses, minimum part load, ramp rates, spinning reserve) as well as economic aspects (fuel, start-up and shutdown costs, capacity expansion, investment options, cost of capital).

To facilitate experiments under numerous scenarios, model parameters and outcome variables can be specified as (conditional) arithmetical expressions. A rolling time horizon and automatic scaling of time series data facilitate simulation of unit commitment over thousands of time steps on any discrete time scale. Ex-post cost price calculation affords inferring market prices and producer surplus.

The Linny-R modeling tool provides an intuitive WYSIWYG model editor for networks, datasets, charts, and experimental designs. Easy navigation through the cluster hierarchy, and seamless transition from editing a model to executing it, facilitate interactive participatory model development. The software is platform-independent, and runs in all modern internet browsers. It is open source, available under the MIT license (https://github.com/pwgbots/linny-r), and can be linked to any MILP solver.

Linny-R has been used by undergraduate students with only basic Operational Research training to simulate industrial ecosystems and (transboundary) energy markets, assess the flexibility and vulnerabilities of industrial clusters, and identify robust investments in network components, storage and power-to-X. Examples of these models (Antwerp industrial cluster, network expansion planning, effects of interconnection on regional e-prices and producer surplus) and their output will be presented to demonstrate that the graphical notation is indeed easy-to-learn for people with limited training in OR.

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Learning with case studies: scientific contributions and solutions applicable to water-Energy-food-waste Nexus in the Global South

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Maryegli Fuss [1], *Laura-Patricia Oviedo-Toral* [1], *Davi François* [1], *Witold-Roger Poganietz* [1]

1. Karlsruhe Institute of Technology

The development of the Global South is awakening aspects reminiscent of past experiences since it has become the core of several global challenges and UN Sustainable Development Goals (SDGs). The number of studies and projects is increasing and generating ambiguities and diversified conflicts when practical work occurs. The ambiguity is, for example, to the poverty rate in global food producers' countries like Brazil and India. The clashes in research areas have already reached extreme cases because of misunderstandings about the nature and resilience of native and indigenous people in Latin America. The divergence of knowledge, attitudes and expectations reflects how transdisciplinary research differs in the global North and South. The consequences are limitations and stagnation in organizing society and responding to environmental challenges.

This study introduces the tripartite transdisciplinary framework (TTF) as a constructivist approach to support effective problem-solving in the global South by increasing communication and collaboration in sustainability in a coherent whole. It is a scientific contribution to existing concepts in transdisciplinary research. It was elaborated based on the knowledge acquired after the performance and observation of different case studies (finished and in progress) carried out in the Global South, specifically in Brazil, Uganda, Bolivia, Mexico, Chile, Indonesia, India and Ghana. Technically, all cases concentrate on communities with initiatives compatible with SDGs on clean water access & sanitation, mobility, energy access & poverty and waste management to reach the approaches for the water-Energy-food-waste Nexus. Two relevant research questions are worth analyzing: What do these cases have in common that can be fundamental to promoting collaboration in sustainability? Why do we need to learn about these communities?

This study was conducted over eight years through dialogues, interviews, quantitative analysis, implementation of renewable systems for the water-Energy-food-waste Nexus, observation & reflection and post-workshops with academics and non-academics. The human connection with nature, i.e. feelings for nature, the socio-environmental impacts suffered, and family ties are the three common aspects identified among the cases as fundamental to be recognized in the sustainability collaboration process for the Global South communities. Combining these three aspects has created personal values and beliefs (e.g., environment and traditions). Personal values and beliefs have become invisible or ambiguous when international projects occur because the official governmental narrative (incompatible in many cases with the local reality lived within the communities) or global socio-political system is taken as a reference. For this reason, TTF proposes a holistic analysis to understand the roots of the problems created in communities, cities or even nations in the Global South. The holistic analysis integrates the known present and the predicted future with feedback on the lived past. The lived past combines historical and psychosocial indicators to assess those values and beliefs to create relational and emotional systemic activities. Systemic relational and emotional activities leverage what is strongest in the communities to naturally achieve a common purpose (i.e., needs) through developing their capabilities. Available narratives and visual & oral histories are examples of methods to assess historical and psychosocial indicators taken in the TTF to understand existing values and beliefs. The present combines technology and system analysis on empirical bases. Scenario methods give the future perspective. The Integrative Concept of Sustainability (ICoS) of the German Helmholtz Research Association brings coherent and temporal connections through specific criteria of justice, global perspective and a human-centred approach.

Water Circularity Indicator: Development and Application to a Pimpri-Chinchwad City in India

Monday, 3rd July - 12:28: Circular economy (short presentations) (A1.44 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Nikita Kakwani [1] ***, Pradip Kalbar*** [1]

1. *Indian Institute of Technology Bombay, Mumbai*

The concept of Circular Economy (CE) in the water sector has gained traction in the research community, especially since the past decade. The prime reason for the increased attention is rapid depletion of available water resources coupled with water scarcity. Implementing CE strategies followed by monitoring has become crucial for achieving global and national water circularity targets. Several frameworks and indicators have been developed in this regard; however, no consensus has reached yet. In the present work, a novel **"Water Circularity Indicator (WCI)"** is developed to promote, assess, manage and improve the water circularity of a system. WCI is a modified form of Material Circularity Indicator (MCI) developed by Ellen McArthur Foundation and Granta design. Similar to MCI, WCI provides a value ranging from 0 to 1 where 0 indicates a linear water system and 1 indicates a circular water system. MCI is based on Reuse and Recycle strategies of CE, whereas WCI is inclusive of five strategies i.e. **Reduce, Reuse, Recycle, Reclaim and Restore**. WCI involves the evaluation of virgin water consumed inside the system boundary and total water going out of the system boundary to assess circularity. The ultimate goal is the urban water mass balance by **reducing virgin water consumption and wastewater generation** while increasing the water circulation inside the system boundary. WCI is then applied to Pimpri-Chinchwad city, one of the fastest-urbanizing cities in India. It is a major industrial centre of the country, accommodating major Indian automobile companies, pharmaceutical companies, small and medium enterprises, and many other national and multinational companies. The Pimpri-Chinchwad Municipal Corporation (PCMC) manages the city by providing infrastructural services to citizens. In this study, **WCI is evaluated for six scenarios** to assess and understand the water circulation potential of PCMC region and plan future interventions to promote circularity. Furthermore, the Government of India also promotes CE in the water sector and urban water balance through the ambitious Jal Jeevan Mission (Urban) (JJM(U)) by 2030. Hence, starting from the current scenario, i.e. for 2022 (Scenario 1) followed by 2030 and 2045 (Scenario 2 and 3) based on the water management plans by PCMC. Scenario 4 for 2030 as per JJM(U) targets. Two scenarios for 2030 and 2045 (Scenario 5 and 6), as recommended by authors considering the land-use and future growth by estimating the city's potential to reduce, reuse, recycle, reclaim or restore strategies. The results from the study indicate that the **WCI value will increase from 0.51 in Scenario 1 to 0.90 in Scenario 6**. Also, in the current scenario i.e. 2022, PCMC is providing around 535 MLD (Million Liters per Day) of virgin water and by 2045, PCMC will require around **300 MLD more water to cater to the demand**, which is beyond the capacity of available water sources. However, as per Scenario 6, the city only needs around 45 MLD more i.e. around 580 MLD, to cater to demand in 2045 by recirculation of around 350 MLD. **The municipality needs to rethink future infrastructure planning to move towards water circularity.** WCI provides an opportunity for utilities to monitor the status of the urban water cycle and improve the water flows by adopting CE strategies. Thus, the evaluation of WCI for a given system can provide valuable insights to decision-makers in achieving **urban water goals.**

Advancing Sector Footprint Monitoring: Integrating Bottom-Up data into Top-Down Approaches for Estimating the Environmental Impacts of Healthcare

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Michelle Steenmeijer [1]***, Lowik Pieters*** [2]***, Martijn van Bodegraven*** [1]***, Rosalie van Zelm*** [3]***, Susanne Waaijers-van der Loop*** [1]

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In the transition to more sustainable economies, monitoring the footprints of nations is becoming more important to assess whether climate or sustainability targets are met. In recent years, the Netherlands has also set specific climate and sustainability objectives at a sectoral level to drive action and to improve decision-making, since different sectors likely contribute to national climate goals in different ways. Environmentally extended input-output analysis (EEIOA) has been used as a valuable tool to track environmental pressures in consumption and production chains top-down. It is ideal for consistent accounting of environmental pressures and allows for comparisons between nations and sectors. However, using EEIOA for monitoring the progress of sectors has a few limitations. EEIOA is currently not granular enough to report sufficiently on specific mitigation results and are generally not suitable to monitor mid- to long term developments. Furthermore, in EEIOA the footprint of some sectors is affected more than others from aggregation issues and a bottom-up approach may benefit the description of these sectors.

Recently, the Dutch healthcare sector has pledged to monitor its own footprint, as it can significantly contribute to national sustainability targets. Previous research on the healthcare sector footprint has shown one of the major limitations of EEIOA, as it fails to provide detailed insights into the dominant role of pharmaceuticals and other chemicals in the sector's footprint across multiple categories, since it concerns a diverse product group (covering simple soap to process-intensive pharmaceuticals). Ideally, life cycle assessments (LCA) are made for each product and process, but this approach would take too long to complete. To address these limitations, we aim to examine how bottom-up data (LCA and industry data) can improve sectoral footprints for the purpose of monitoring. While it is common to see EEIOA integrated into LCA, the reverse is under-explored. Furthermore, we aim to develop guidelines to facilitate incorporating future research findings into the sector footprint.

In our presentation, we will discuss the opportunities and challenges of integrating bottom-up data into the top-down footprint analysis. We will delve into the different hybridization approaches and their respective drawbacks with regards to data requirements and complexity. We will also discuss the different types of data sources available in literature and practice and their current discrepancies for integration in the top-down footprint, and furthermore outline how data ideally would be reported in future studies for effective monitoring. Our study is critical to advance sector monitoring and provides a starting point for further improvement of the healthcare sector footprint.

Plastics have lower greenhouse gas emissions than their alternatives in most current applications

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Fanran Meng [1], ***Miguel Brandão*** [2], ***Jonathan Cullen*** [1]

1. *University of Cambridge,* ***2.*** *KTH Royal Institute of Technology*

Plastics are arguably among the most revolutionary materials humanity has invented. They are low-cost yet lightweight, durable, and highly customizable, so plastics are widely adopted for use in packaging, construction, automotive and other sectors. It was estimated that the production of plastics increased from 2 Mt in 1950 to 380 Mt in 2015, leading to a cumulative total production of 8500 Mt of virgin plastics. However, plastics have become controversial due to their production from fossil fuels, emissions during production and disposal, potential toxicity, and leakage to the environment. Calls to move away from plastic products towards non-plastic alternatives are common. However, the question of whether suitable alternatives with lower environmental impact exist is often overlooked.

This paper examines the climate change impact of plastic products versus their alternatives. We assess 16 applications from across different sectors where plastic use is common—packaging, building and construction, automotive, textiles, and consumer durables. These sectors account for about 90% of global plastic volume. Among the applications assessed, plastics incur lower GHG emissions than the alternatives in 15 of the 16 applications. The use of plastic in these 15 applications results in 10% to 85% less GHG emissions than non-plastic alternatives over the product lifecycle. Furthermore, in some applications, for example, food packaging, there are no suitable alternatives to plastics. Our results demonstrate that avoiding plastic products in favour of current non-plastic alternatives is not a viable solution for reducing GHG emissions. Efforts should instead focus on reducing demand for plastics through more efficient use and improved environmental performance of plastics, targeting net-zero emission across the lifecycle, increasing recycling rates, and eliminating leakage to the environment.

What is the Greenest Last-mile Delivery Option for Consumers' Online Purchases

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Jasmina Burek [1]**, *Davide Alessi*** [2]

1. University of Massachusetts Lowell, 2. University of Trento

Before COVID-19, only 9% of global customers were shopping online for general merchandise and groceries weekly. However, after the pandemic, e-commerce delivery increased by 35%. In 2022 there were more than 266.7 million digital buyers in the United States. This demand increased last-mile delivery services and contributed 60% of annual expenditure in the United States and 80% of total greenhouse gas emissions from freight transportation. This high-rising industry began implementing more environmentally friendly solutions. For instance, Amazon is implementing electric last-mile delivery vans to reduce its impact. Still, e-commerce sustainability has not yet been assessed deeply. Given the great impact that transportation in e-commerce has, the objective of this study is to perform an environmental assessment of the existing and novel delivery options using life cycle assessment (LCA) and to propose solutions that will improve the delivery sector's sustainability. Also, for consumers, we developed a tool to assist them in making informed decisions that will help reduce GHG emissions of their online purchase delivery. First, we compared two last-mile delivery methods: (1) home delivery and (2) pick-up stations. We used a case study based on the city of Lowell, Massachusetts, USA. These two delivery scenarios considered two delivery options - fast delivery and standard delivery. In addition, we developed scenarios for non-refrigerated and refrigerated trucks. Using SimaPro software databases and the information from the literature, we created four scenarios – home vs locker point delivery and express vs standard delivery - and run a life cycle assessment for each of them. The results showed that the greenest delivery option is to receive the package at the closest locker point and go there on foot, with a resulting emission of 0.4 Kg of CO2-eq. The home delivery option with standard speed places not far from the previous option, resulting in 0.53 Kg of CO2-eq. This result comes close to the locker option due to the optimization level reached by the delivery companies. The 1-day delivery option emits more than double GHG emissions (up to 1.15 Kg of CO2-eq) compared to standard delivery. The worst-case scenario is using a vehicle to reach the locker point, with almost 2 Kg of CO2-eq emitted. Additionally, the study tests another scenario that uses electric trucks, but the result shows that it is not as green as one might imagine. In fact, for the home delivery case in Lowell, the process emits 0.73 Kg of CO2-eq. Different results emerge if electricity coming from greener sources is used. This is the case for Washington State. In this scenario, the kilograms of CO2-eq emitted are 0.44. The takeaway of this research is that standard deliveries have almost half of the express deliveries' footprint for each order and the pick-up option is the greenest only if reached without using vehicles. This research opens further studies in this field, in particular for the implementation of electric vehicles and new pick-up lockers.

WasteFootprint: A Python tool in the Brightway2 framework to categorise and quantify waste flows in LCA

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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As the European Union and other governmental bodies strive to transition toward a circular economy — a concept focused on the prevention of waste and the reuse of resources — appropriate tools to identify and quantify waste flows through supply chains are of critical importance. Life Cycle Assessment (LCA) is a crucial tool for this, given its capacity to pinpoint hotspots of environmental impact throughout the life cycle of products and services, those where the implementation of circular principles could be most effective.

Methods of calculating an impact factor based on an aggregated waste score for a given functional unit are newly available in Ecoinvent 3.9 (FOEN (ed.)., 2021). However, the lack of standard methods allowing for a flexible quantification of specific waste types across datasets, such as hazardous materials or materials with particular End-of-Life (EOL) pathways (e.g., incineration, composting, or open-burning), limits our ability to effectively prioritise further research and to develop strategies to capture circularity opportunities. The authors believe that a detailed mapping of waste flows could inform strategies for environmental impact reduction, since waste production contributes strongly to overall environmental impacts (Reinhard et.al., 2019).

In this study, we present a Python-based tool that enables the aggregation of mass and volume for all waste exchanges, and the creation of flexible categories to differentiate between waste types and End-of-Life (EOL) handling using (in this case) the Ecoinvent 3.9 cutoff database.

This tool provides a method for the calculation of waste footprint impact category results, differentiated by the type of waste handling. Furthermore, the tool facilitates rapid investigation and identification of waste hotspots, enabled by standard contribution analysis and Sankey diagram visualisation tools. The authors consider this a crucial step in addressing the deficit of Life Cycle Assessment (LCA) methods that consider waste flows in the evaluation of a product or process' circular economy potential.

We identified all Ecoinvent technosphere exchanges that produce waste and further classified them into non-mutually exclusive categories, such as its destination (i.e. dumped, incinerated, etc.), hazardousness, and form (solid vs. liquid). To quantify the waste footprint of a product, we cloned the technosphere exchanges as biosphere exchanges and aggregated them into matching impact categories in the Life Cycle Impact Assessment. This enabled us to compare waste footprints across products and identify hotspots of waste linked to particular life cycle processes.

In our simplified test case of six battery types, we were able to identify 'waste hotspots' and distinguish the major sources of contribution to waste generation on a process-level. One conspicuous result from the case study (and potential direction for further work) is that many waste flows are tied to processes lacking a clear EOL pathway. Further development of this tool could involve developing an algorithm using identifiers of each background waste process to predict where these uncategorised wastes land in their EOL management.

LINK TO FOLDER CONTAINING REFERENCES, SUPPORTING FIGURES AND DETAILS TO THE CODE:

https://leidenuniv1-my.sharepoint.com/:f:/g/personal/mcdowallsc_vuw_leidenuniv_nl/EuWOVGeCHH9Im4_gtrVpEGoB1EfqaVo

Sustainability assessment of heavy duty transport using the multi-criteria analysis (MCA)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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As the world is currently facing many different environmental challenges, such as climate change, scarce water resources or the loss of biodiversity, it would be desirable to address them with solutions that resolve more than one problem simultaneously. The transportation sector is an important industry in many developed and emerging economies, which impacts people's life quality, health, and the surrounding environment. The road freight transport of goods is responsible for a significant share of GHG emissions around the world. To meet the EU decarbonization targets, more sustainable truck alternatives must replace currently used fossil-based fuel technologies. However, choosing the preferable technology for long-haul units that would incorporate renewable fuels might be difficult since sustainable performance is a multi-faceted issue and most of the time it does not come with a straightforward answer. Former research shows a potential need for improvement in knowledge and supportive methods on how sustainability assessments can support decisions. To address this problem, a multicriteria analysis (MCA) method was developed which can be used as a decision support tool which would potentially facilitate different actors to make more informed and conscious choices, which at the same time consider a broad range of sustainability indicators. This method aims to assess the feasibility and sustainability of a variety of truck and fuel types that are currently on the market or that might be entering it soon. The methodology was developed through an iterative and participatory process, which included the participation of actors, stakeholders and experts from different fields and sectors such as truck manufacturers, logistics, goods transport companies, fuel producers and suppliers and researchers. The assessment consists of five main criteria which are further divided into fifteen different indicators covering a broad system perspective and sustainability performance. In a further study, various trucks and fuel types will be identified (such as diesel, electrically-chargeable, hybrid electric, HVO, CNG, LNG, biomethane, ethanol and FAME) and assessed using a five-point scale.

Analysis of the transport sector to establish deep-decarbonization strategies in Peruvian cities

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Claudia Cucchi [1], ***Ian Vazquez-Rowe*** [1], ***Ramzy Kahhat*** [1], ***Félix Cabrera*** [1], ***José Carlos Silva*** [1], ***Patricia Urteaga*** [1]

1. *Pontificia Universidad Católica del Perú*

The concentration of human population growth in cities and its consequences on urban metabolism are increasingly responsible for the global carbon emergency the world is facing. Peruvian cities have been some of the fastest-growing urban areas in Latin America and the world since the mid-20th century and represent over two thirds of the country's GHG emissions (excluding those derived from land use change). However, changes in the urban mosaic of Peruvian cities have been erratic in terms of adapting to the challenges described in the Sustainable Development Goals (SDGs) and the more climate-related nationally-determined contributions (NDCs), the latter fully linked to climate mitigation and adaptation actions. Unfortunately, the NDCs proposed by the Peruvian government to comply with the Paris Agreement are being displayed at a relatively low pace. In fact, a series of life-cycle studies have raised concerns about the actual trade-offs that could occur when these NDCs are implemented, with hidden climate emissions potentially emerging in other geographical areas. Therefore, it is imperative that Peruvian institutions develop a revised set of carbon mitigation measures that are aligned with deep decarbonization, in order to generate a nationally-based pathway that allows much deeper carbon emissions cuts once the 2030 climate-oriented steps are fulfilled. More specifically, deep-decarbonization requires sector-by-sector specific actions in which low-carbon activities are progressively integrated in larger international markets. In this context, the main objective of the current project is to establish pathways for deep-decarbonization objectives in the context of Peruvian cities. For this, we have selected the transport sector, as it is responsible for over one third of GHG emissions in urban environments in Peru. The methodology applied combines the use of Life Cycle Assessment (LCA), Material Flow Analysis (MFA) and meso- and microsimulation traffic models, as well as auxiliary methods in order to understand traffic behaviour and related environmental impacts. Thereafter, a set of scenarios, in which we propose a combination of new emerging technologies and strategies for social behavioural change, test the capacity of attaining deep-decarbonization results in this particular context.

Environmental Impacts of Residential Relocation in the Autonomous Vehicle Era

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Kendrick Hardaway [1], ***Hua Cai*** [1]
1. *Purdue University*

Motivation

Autonomous vehicles have the potential to make travel time less inconvenient by allowing riders to work, engage in leisure, or other activities rather than drive. This effect could have implications for travel behavior and, subsequently, how people choose where to live. The study of this socio-technical system has major inferences for our environmental impacts. First, transportation already contributes a significant amount of greenhouse gases. However, if people decide to change their travel behavior given an autonomous vehicle (e.g., more frequent or longer trips), then emissions could increase. On top of this impact, exacerbating urban sprawl would have negative consequences for biodiversity, resource consumption, and greenhouse gas emissions. For us to make sure autonomous vehicles are implemented in line with our short- and long-term environmental targets, we must identify and address the environmental feedback loops I point out in my simulation. This work provides a first step toward doing so.

Methods

Using Miami, Florida, as a case study, I have created an agent-based simulation that anticipates possible future outcomes of where people will choose to live if they have access to autonomous vehicles. Some research indicates that people may live farther from the city center, thus exacerbating urban sprawl while others suggest infill due to less parking needs. This is because trips become less of a hassle when the driver can engage in entertainment or work activities rather than driving. However, these studies have been limited to a very short temporal scope. My simulation allows a decade of time to unfold, and it models how people might choose to adopt an autonomous vehicle, how their travel behavior would subsequently change, and how both those influences could impact where people prefer to live (and thus where development occurs). In so doing, I capture long-term feedback loops that often go ignored in environmental assessments of autonomous vehicles. This is the primary novelty of my simulation.

Anticipated Results

Anticipated final results will include the change in total VMT and the change in housing demand throughout the city. I expect to quantify the type of households that move most often, the change in average vehicle occupancy, and overall shift in population density. These results should help urban planners and decisionmakers weigh choices about preparing infrastructure for autonomous vehicles, especially as they might impact environmental impact goals. Preliminary results suggest that the long-term impacts of AV adoption could have detrimental environmental impacts from the perspective of travel behavior and residential relocation.

Establishing the potential contribution of public transport to climate neutrality based on high resolution urban environment modeling

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Patrícia Baptista [1]***, Ricardo Gomes*** [1]***, Francisco Plácido*** [1]***, Paulo Ferrão*** [2]

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Considering the need for decarbonizing the transport sector, a strong behavioral change must be promoted towards the adoption of efficient technologies, but mainly to foster the use of more efficient transport modes, namely public transportation (bus, metro, train, etc). The use of public transportation is highly influenced by the quality and level of service, but also by user related constraints (e.g. mobility constraints, typology of area of residence, willingness to walk to public transportation, etc.).

Consequently, this paper aims at quantifying the potential CO_2 emission savings from adoption scenarios for public transport. The work creates a general methodology for evaluating the CO_2 emission savings from shifting trips performed by private vehicle to either buses or trains, having as a starting point the already established accessibility methodology defined by the Transport for London. Based on high resolution geographical modeling of a neighborhood, different modal shift scenarios for buses are evaluated, based on socio-economic characteristics, accessibility indicators and mobility pattern requirements.

For different levels of willingness to adopt public transport (e.g. area with higher accessibility indicators to bus stops, shorter trips and higher levels of educations are more prone to change compared to area with remote access to bus stops and longer trips per day), the CO_2 emission savings from shifting from private cars to public transportation will be computed, enabling the quantification at a building or neighborhood scale of potential impacts.

These results provide important insights on how to redesign supply to be more adequate to demand, both in terms of public transport stops, but also in the identification of areas more suited to tailormade on-demand services.

This work is developed as part of the Project BE.Neutral – Agenda de Mobilidade para a neutralidade carbónica nas cidades, contract number 35, funded by the Resilience and Recovery Plan (PRR) through the European Union under the Next Generation EU.

Critical raw-material requirements for lithium-ion batteries for the electrification of the Swedish passenger car fleet

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Simon Davidsson Kurland [1], ***Johannes Morfeldt*** [2], ***Daniel Johansson*** [2]

1. Uppsala University, 2. Chalmers University of Technology

Electrification will be a crucial part in decarbonizing the highly fossil fuel-dependent transport sector. Electric vehicles (EVs) are already reaching significant market shares of passenger cars in many countries, including Sweden. One commonly discussed constraint to a rapid growth of EVs is the availability of potentially *critical materials* used in lithium-ion batteries. However, the quantities of these materials that will be required depend on a wide range of different factors, many of which are highly uncertain.

The aim of this study is to explore the potential future demand of *critical materials* for lithium-ion batteries in Sweden under varying circumstances and to highlight strategies that can decrease the required amounts of materials facing supply risk. Focusing on a single country as a case study enables detailed assumptions on the development of the vehicle fleet, trends regarding technological choices, and policy developments.

The Swedish vehicle fleet is modeled with a fleet turnover model introduced by Morfeldt et al. (2021). A range of scenarios for future battery material demand is explored by making different assumptions on future travel demand, which have large impacts on the number of passenger cars that will be required in the future, in combination with different plausible assumptions on vehicle size, battery capacity per vehicle, as well as the material intensity of these batteries. Among the set of all the scenarios created, four widely different scenarios are chosen for further analysis regarding total annual requirements of cobalt, lithium, and nickel. By highlighting the differences between the scenarios, it is possible to visualize choices policy makers and industry can make to minimize the required amounts of materials.

Results show that limiting the number of passenger cars, but also the vehicle size and corresponding battery capacity, has a great potential to limit the quantities of required battery capacity and associated raw materials. By choosing cobalt and nickel free battery chemistries it could be theoretically possible to eliminate, or significantly decrease, the demand for cobalt and nickel for batteries, but the lithium demand would remain fairly constant.

While many similar studies focus on investigating the potential for recycling and future circular economy measures, the focus here is on the near term, i.e., the coming decade or two, before any significant amounts of battery materials will reach end-of-life. More research is needed into investigating under which circumstance availability of materials such as cobalt and nickel will limit growth of electrification of the transport sector and when it may cause problems for individual actors.

Morfeldt, J., Kurland, S.D., Johansson, D.J.A., 2021. Carbon footprint impacts of banning cars with internal combustion engines. Transportation Research Part D: Transport and Environment 95, 102807. https://doi.org/10.1016/j.trd.2021.102807

Development and assessment of biodegradable and compostable primary batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Joan Muñoz-Liesa [1], ***Miquel Sierra*** [2], ***Marina Navarro-Segura*** [3], ***Juan Pablo Esquivel*** [4], ***Laura Talens Peiró*** [1]

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Portable primary batteries production and consumption is increasing worldwide due to the ever-growing market of electronic devices and the irruption of internet of things. Primary batteries are made from non-renewable and scarce resources that are associated to complex value-chains some of them associated with high supply risks and relevant environmental impacts at their end of life. Importantly, current portable primary batteries are not designed to fit devices' energy needs, and therefore in many cases they are oversized. This leads inevitably to the nonoptimal and inefficient use of the materials and energy capacity of these devices. The project BIDEKO aims to develop new batteries focusing on a more efficient use of resources to fit specific final device energy needs. One of the additional goals is to design these batteries to be compostable and biodegradable, thus lifecycle environmental impacts generated by current conventional batteries are avoided as well.

The methodologies used for the design of these batteries combine technical information based on the compatibility of materials for the correct operation of the battery, environmental information regarding the materials and biodegradability testing to ensure their minimal impact at the end of life. All this information is combined to assess their potential environmental impacts. To do so, a detailed analysis of all the stages involved in their lifecycle is performed, including the raw material selection, manufacturing process, demanded energy capacity, operational time, and disposal. All these stages need to be assessed to ensure that new batteries will have lower environmental impacts than conventional batteries along their entire life cycle. This work presents the eco-design process followed to assess a first prototype of a biodegradable battery, referred to as BIDEKO 0. The steps include: (i) to define and test an eco-design methodology specifically developed for future biodegradable batteries; (ii) to size batteries' energy capacity to meet energy demands; (iii) to avoid end-of-life environmental impacts currently occurring in primary batteries by designing them to be biodegradable; and (iv) to quantify environmental impacts, hotspots and potential trade-offs compared to current market primary batteries. Preliminary results show that the battery case and membrane parts are responsible for more than 60% of impact category results analyzed. In both cases, the stages with greater share are the manufacturing processes. This suggests that improved manufacturing techniques should be implemented when planning an upscale to industrialized manufacturing process. When the proposed biodegradable batteries are assessed using as functional unit kWh of stored energy likewise conventional batteries, their potential environmental impact overpasses that generated by conventional batteries, mainly due to a lower energy capacity. We therefore recommend a deeper discussion regarding functional unit definition for the study of these new batteries, and to move the focus from battery storage to energy end-use of primary batteries, since this might have great influence on environmental impacts. Results also indicate that biodegradable batteries can generate greater environmental savings especially in locations where recycling infrastructure for conventional batteries is lacking. Overall, these results provide new methodological insights and open the path towards the development of more sustainable future portable batteries.

Towards a circular economy of water- Integrated process modeling, technoeconomic analysis, and life cycle assessment for anaerobic membrane bioreactor platform for wastewater management

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wednesday, 5th July - 11:15: Water 2 (B0.16 KOG)

Madison Kratzer [1], ***Prathap Parameswaran*** [2], ***Vikas Khanna*** [1]

1. University of Pittsburgh, 2. Kansas State University

One of the key tenets of the circular economy is minimizing resource extraction by fully recovering resources from streams that are traditionally considered waste. Wastewater streams from different sources contain recoverable products such as energy and nutrients. Recovering these resources offers a pathway for minimizing the extraction of virgin resources its associated environmental impacts. Nutrients such as biologically active nitrogen and phosphorus derived from waste streams are of particular interest as these are typically obtained from non-renewable resources with high life cycle environmental impacts. Concentrated animal feeding operations (CAFOs) contain high strength waste streams from large numbers of closely reared animals that contain significant amounts of nitrogen, phosphorus, and organics. Hog farming CAFOs produce relatively consistent waste streams because these operations are in confined buildings. The current dominant practice for swine wastewater management is a combined conventional activated sludge (CAS) and anaerobic digestion (AD) platform. The standard CAS and AD platform requires a large energy input for aeration and does not include nutrient or volatile fatty acid (VFA) recovery. Recent research has shown potential for treatment of swine wastewater using an anaerobic membrane bioreactor (An-MBR) platform which allows for the capture of biogas, VFAs, nitrogen, and phosphorus. An An-MBR system couples anaerobic digestion and membrane separation to allow for long solids retention times in a small footprint and is capable of producing high quality effluent for discharge. An-MBR systems allow for high carbon conversion and recovery of fermentation products. Existing work in this domain has focused on evaluation and optimization of singular unit processes in isolation. A holistic systems approach to evaluating the environmental and economic performance of the An-MBR platform is needed to guide research and development and provide quantitative comparisons of the system to traditional treatment methods.

This work presents an optimization-based decision-making framework for the evaluation of economic and environmental impacts of the treatment of swine wastewater in an integrated resource recovery system. A process-based model of unit operations which included an An-MBR, VFA recovery, phosphorus recovery through coagulation and flocculation, nitrogen recovery through adsorption, and a final wetland polishing step was first created. These detailed first principles-based models allow for evaluation of a wide problem space rather than ad-hoc consideration of candidate treatment trains. Optimization for the mixed integer nonlinear programing (MINLP) problem is conducted in Pyomo using the IPOPT algorithm. The integrated process models were utilized to perform detailed life cycle assessment (LCA) and technoeconomic analysis (TEA) of the An-MBR system. Preliminary results show that the An-MBR platform is comparable in cost to CAS and AD treatment on an economic basis through value of captured nutrient products offsetting high capex costs of the An-MBR system. An evaluation of the return on energy investment of the isolated An-MBR system showed for typical swine wastewater return on energy investment was approximately 1.4, which is comparable to biodiesel. VFA separations by distillation have been identified as a key source of environmental impacts in the LCA. Detailed sensitivity analysis has been performed around key variables including energy for membrane cleaning, ambient temperature, removal of carbonate alkalinity from the system prior to phosphorus treatment, and the specific composition of the swine wastewater to quantify their impact on LCA and TEA results. The implications of the findings and challenges for developing circular economy solutions for wastewater streams will be discussed.

Deriving Product Nutrient Inventories from Nitrogen and Phosphorous Flow Accounting of U.S. Agricultural commodities

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Christine Costello [1], ***Lucas de Lima Casseres dos Santos*** [2], ***Mikaela Algren*** [3], ***Amy Landis*** [3]

1. Pennsylvania State University, 2. The Pennsylvania State University, 3. Colorado School of Mines

Crop- and animal-based commodities are the most significant cause of nitrogen and phosphorous use and corresponding impacts in the United States (U.S.). Nutrients have exceeded local and regional boundaries in many of the world's watersheds. This abstract shares the progression over the last ten years of modifying the Net Anthropogenic Nitrogen and Phosphorous Inputs (NANI, NAPI) accounting tool (Hong et al., 2011; Howarth et al., 2012), now termed CSNAPNI (Commodity-specific NAPNI). CSNAPNI modified the original accounting tool to relate crops to livestock (N: Costello et al., 2015, P: Algren et al. 2022) and account for the corn ethanol industry and use of dried distillers grains (DDGs) in livestock feed (Algren et al., 2021). CSNAPNI estimates annual net N and P flows for 16 crop- and 6 animal-based commodities at the county-scale in the contiguous U.S. (3,111 counties ranging from 5.2 km2 to 51,950 km2 and averaging 1,208 km2). National-scale N and P per unit of production (i.e., per kg, per kg protein, per kcal) were calculated using CSNAPNI output to estimate footprints and life cycle inventory/impact assessment comparisons. Global warming potentials, land use, and eutrophication potentials were found to be similar to those estimated using life cycle assessment at the farm-scale in the literature, suggesting that for commodities, this approach provides a reasonable estimate of N & P inputs at the unit scale (Costello et al., 2015). Ethanol and DDGs were included in CSNAPNI by allocating N and P inputs to corn to each product and ultimately the animal-based commodities to which DGS flowed. With allocation of N inputs between ethanol and DGS, N inputs to ethanol per volume were reduced by approximately 30% relative to previously reported values. N inputs to animal products decreased over time with increasing inclusion of DGS in animal diets and reduced contributions from other crops; N inputs per unit protein in beef and milk products were reduced by 19% and 13%, respectively, as ethanol production in the US increased from 1997 to 2012. P inputs to animal products, which are driven in large part by mineral P supplementation, were insignificantly affected with DGS inclusion in animal diets (Algren et al., 2021; Algren et al. 2022). The updates to P flows in CSNAPNI to ensure mass balance from crops to livestock resulted in an update to assumptions about livestock consumption of P supplements, finding that supplements can make up to 60% of embodied phosphorous for chicken meat and 75% for turkey meat, if digestibility of P could be increased and reduce the input of P by 25%, up to 30% of NAPI to the contiguous U.S. could be reduced (Algren et al., 2022). Currently, the lab is working on a Chesapeake Bay Watershed (CBW)-specific version of CS-NAPNI (CBW-NAPNI). The CBW-NAPNI framework includes updated fertilizer application rates, changes in livestock diets to reflect practices in the Northeastern U.S. (smaller farm size, more use of corn silage), and smaller spatial units of analysis, rather than 203 counties, 1902 spatial units representative of land-river segments in the CBW estimate NANI and NAPI. Further, the landcover per unit is represented with 30mx30m satellite data as opposed to U.S. Dept. of Agriculture production data for the county. Preliminary results for the same 16 crops and 6 animal-based commodities will be presented and compared to national and farm-scale LCA estimates.

Material efficiency and carbon emission reduction strategies of passenger vehicles: a case study of the Yangtze River Delta region

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Huimei Li [1] ***, Stefan Pauliuk*** [2]

1. Faculty of Environment and Natural Resources, University of Freiburg, 2. Freiburg University

Passenger vehicles, as the primary mode of personal transportation, account for nearly half of China's transport CO_2 emissions. To achieve carbon neutrality by 2060, a deep and rapid decarbonization of this sector is required. Improving the material efficiency of vehicles and transport infrastructure is essential for decoupling resource depletion and associated environmental pressures from economic development. Although some modelling studies have been conducted to estimate future energy consumption and CO_2 emissions from Chinese passenger vehicles, most of them have been focused on a national level. By taking into account regional disparities, such as population density, topography, and disposable income, a comprehensive assessment of the material metabolism and carbon emission reduction potential of the vehicles at the provincial scale can further provide a scientific basis for policy formulation in circular economy and sustainable development.

The Yangtze River Delta region is the largest economic and trade city cluster in China and occupies a very important position in the country's development. The study of carbon emission reduction from passenger vehicles in this region is of great significance for climate change improvement and sustainable development. Based on the dynamic material flow analysis method, we construct a provincial-level RECC model to project the passenger vehicle stocks, material demand, energy demand and CO_2 emissions in Shanghai, Jiangsu, Zhejiang, Anhui. The results show that: 1) The ownership of passenger vehicles in these four provinces show a pattern of rapid growth followed by gradual saturation. From 1950 to 2020, passenger vehicles ownership has shown exponential growth, but after 2030 the number of passenger vehicles in Zhejiang province slows down and reaches saturated around 2040, slightly ahead of Shanghai and Jiangsu province, while Anhui province is the last to follow this trend. 2) The material composition of the stock is changing, with the proportion of ordinary steel and iron gradually declining and being replaced by high-strength steel and aluminum metals. The demand for other strategic metals and rare metals will continue to rise. 3) Driven by existing policies, carbon emissions from passenger vehicles in use will peak around 2030. Next to energy efficiency and low-carbon energy supply, material efficiency will offer additional emission reduction opportunities in the passenger vehicle sector. And in more specifically, ridesharing and car-sharing will provide additional opportunities to reduce emissions. Material efficiency will have a greater impact on passenger vehicles' carbon reduction in Anhui Province compared to the other three provinces.

Comparative Analysis of Energy Transportation Modes: Economic and Environmental Considerations for the Low-Carbon Energy Transition

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ella Jennings [1], *Jonathan Cullen* [1]

1. University of Cambridge

The Climate Emergency requires us to forcefully overhaul our global energy system, involving drastic transitions in primary energy sources and in electrification. Since renewable energy resources do not align geographically with fossil fuel reserves, these transitions will profoundly impact the geographic dynamics of global energy supply chains. Consequently, countries worldwide will need to expand and adapt their energy transportation infrastructure to accommodate these transformative changes. Thus, the ability to transport energy efficiently, reliably, and with minimal environmental and economic costs assumes paramount importance within the context of the low-carbon energy transition.

Energy can be transported through various modes, characterised by type of energy carried, cost, efficiency, flexibility, and carbon intensity. Chemical energy may be transported in pipelines (fluids) and in tankers (solid and fluid), electrical energy flows through wires, nuclear fuel is transported with various vehicles, and thermal energy is transported through pipes such as in district heating. This study presents a comparative analysis of these transportation modes, evaluating the economic and environmental costs using the metric of Joule-kilometers. The utilisation of the Joule-kilometer metric enables a direct comparison between modes based on the amount of energy transported over a set distance. The analysis considers construction, operational, and maintenance expenses, embodied energy, and operational losses. Notably, thermal energy transportation exhibits lower performance based on these metrics due to its relatively low energy output rate, whereas nuclear energy performs best, with the lowest costs per J-km due to the high energy density of nuclear fuel.

In addition to the functional analysis, the study investigates historical trends in modal use, shedding light on past energy transitions. The examination of data pertaining to the quantities of energy transported through each mode over time facilitates an understanding of the evolving dynamics in global energy transportation. Factors influencing these trends include technological advancements, shifting energy resource availability, and globalisation.

The outcomes of this study provide clarity to our understanding of energy system studies, by specifically examining the transportation of energy. By offering insights into the efficient and sustainable transport of energy on a global scale, this research can support informed decision-making. It leads onto research into pivotal questions to the low-carbon energy transition such as: What new infrastructure is required for future energy transportation and what carbon emissions will be associated with providing this?

A life-cycle perspective on the benefits of renewable electricity generation in the EU27

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 10:15: Ex-ante LCA 2 (C0.06 KOG)

Evert Bouman [1], ***Francis Barre*** [1], ***Gaylord Booto*** [1], ***Babak Ebrahimi*** [1]

1. Climate and Environmental Research Institute NILU

Introduction

The generation of electricity and heat contributes significantly to annual anthropogenic greenhouse gas (GHG) emissions of the European Union (EU). Despite multiple demonstrated benefits for human health and the environment associated with the reduction in fossil fuel use for energy, the increased use of renewable energy sources (RES) is not impact free and may come at a cost to the environment. Here, we present the benefits and trade-offs of the use of RES for the production of electricity for the Member States of the EU27 from a life-cycle perspective.

Approach

We construct a parametric life-cycle model of electricity generation accounting based on a collection of life cycle inventories (LCIs) describing archetypical electricity generation processes for a total of sixteen different renewable and non-renewable energy sources. Using available national statistical data on fuel consumption, fuel characteristics, and gross electricity production, sourced from Eurostat, these LCIs are adapted to create inventories specific to (renewable) energy source, year, and Member State. These specific LCIs are then used to calculate potential environmental impact intensities for electricity generation, distinguishable by energy source and Member State, and for any given year in the period 2005-2020. Based on an energy system scenario specific to the EU27, we additionally calculate life-cycle impacts in the period 2020-2050 at the same resolution.

Main results

Life cycle impact intensities for electricity production are found to differ considerably across energy conversion and between Member States and years, driven by differences in fuel conversion efficiency and capacity utilization. Impact intensities (i.e. impact indicator per unit electricity produced) are driven by a wide range of processes and emissions to the environment, but opportunities exist to decrease impact intensities for singular processes, either by focusing efforts to increase efficiency, or to implement emission mitigation technology. The increased use of RES has led to an absolute decrease in life-cycle impact indicators in the period 2005-2020 for most impact indicators investigated in this study. Annual gross electricity production has remained relatively constant in this period. This decrease is mainly driven by the increased production of onshore wind power and solar photovoltaic power relative to 2005, followed by electricity production from sources such as biogas and solid biomass, and the corresponding reduction in fossil fuel generated electricity. These effects continue to be apparent in a forward-looking scenario post 2020.

The increased use of RES comes at a cost in terms of freshwater ecotoxic impacts (e.g. related to the solar PV value chain) and land occupation impacts (related to the production of solid biomass). These costs are partially compensated for by using a mix of renewable sources to produce electricity, thus dampening the effects of problem-shifting caused in the value chain of singular renewable sources. Diversification of the electricity supply across various types of renewable energy sources is therefore recommended compared to full-scale investment in a single renewable electricity source. Lifetime extension is an option to further mitigate negative consequences from the increased use of non-combustion RES, as impact intensities decrease due to increased infrastructure longevity.

Funding information

This work was funded as part of the European Topic Centre for Climate change Mitigation and Energy and supported by the Norwegian Ministry of Climate and Environment through NILUs basic grant.

Socioeconomic driving forces of industrial hazardous waste generation within industrial supply chain

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Daye Lee [1]***, Junbeum Kim*** [2]***, Guido SONNEMANN*** [3]***, Hung-Suck Park*** [4]

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The South Korean government announced its goal to reduce industrial hazardous waste (IHW) as the first step in its transition to a circular economy. Moreover, as IHW trade between countries is regulated by the Basel Convention, efficient management of IHW within the country has become essential. Despite the need to make concrete environmental policy proposals based on valid reasons, there is still a lack of fundamental information on the determinants of IHW generation, which hinders the effectiveness of IHW policies. Therefore, this study established extended input-output models for IHW to characterize IHW generation and identified the determinants contributing to the increase and decrease of IHW generation in South Korea from 2008 to 2018. The results show that among the seven factors performed by structural decomposition analysis, consumption, export, and direct IHW intensity of ‘Chemical’, ‘Electronic and electrical equipment’, and ‘Basic metal’ are the dominant determinants for IHW growth, while technology change, including technological structure change and direct waste intensity change, of ‘Basic metal’ and ‘Other service’ is the key point for IHW reduction. In addition, in terms of the supply chain, the influence of indirect IHW growth due to exports and consumption expansion contributes almost twice as much to the increase in IHW as direct IHW growth. These insightful findings of this study contribute to navigating a direction for the South Korean government in establishing holistic and customized IHW-related environmental policies by considering the expansion of global system boundaries, technology change, and purchasers’ consumption patterns as dominant factors.

Policy measures towards advancing battery reuse and recycling in Norway

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Chloe Depledge [1]

1. *University of Agder*

The global scale of electrification within the transport sector has generated growing demand for lithium-ion batteries (LiBs), as the most popular form of energy storage. An expanding use of critical materials is required to meet this, raising concerns for the environment and sustainability of supply chains. At the same time, value can also be recaptured from spent LiBs following the initial use phase. Multiple end-of-life (EOL) treatments contribute to closing the resource loop by capitalising on residual battery capacity and the recovery of scarce materials. Due to the early uptake of electric vehicles, Norway is home to significant volumes of LiBs that are rapidly reaching retirement. In the region of Agder, this has driven battery reuse and recycling activities, with numerous actors engaged in this emerging specialisation. However, supporting policies are crucial to further enhance circularity across the value chain.

As part of the ongoing Electric Agder (ELAG) research project, this study focuses on the developing policy mechanisms to incentivise circular change in the Norwegian battery industry. To achieve this, policy analysis assesses the implementation and influence of existing policies which affect EOL scenarios in Norway. Through consultations and complementary surveys, data is collected from key stakeholders operating in battery recycling and reuse sectors. Topics cover barriers to growth, industry needs and provide feedback regarding potential changes based on current policy gaps. The findings are used to present a set of reasonable policy recommendations, with proposed pathways intended to induce more circular practices industry-wide and further develop battery waste markets. By outlining important implications for both policymakers and industry actors, this study is expected to contribute towards a more circular battery value chain in Agder, Norway and beyond.

Consumer Preference Evaluation of Plastic Container Recovery Systems Using Conjoint Analysis

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Atsushi Fujiyama [1]***, Saki Ninomiya*** [1]***, Richao Cong*** [1]***, Toru Matsumoto*** [1]

1. *The University of Kitakyushu*

In recent years, issues surrounding waste plastics have become more serious every year, such as the problem of marine plastic litter, including drifting plastics and microplastics, and export restrictions on plastic waste. In addition, all entities involved, from product design to the collection and disposal of waste plastic, are accelerating their efforts to promote plastic resource recycling and other initiatives (3R+Renewable). In order to recycle resources through material recycling of waste plastics, it is important to establish an effective collection system. The purpose of this study is to quantitatively evaluate citizens' preferences for the "waste plastic collection project" implemented in Kitakyushu City by means of a choice conjoint analysis. Specifically, we conducted a web-based survey of Kitakyushu residents. In addition to the conjoint analysis questions, we asked about personal attributes, awareness of environmental considerations in daily life, and project participation situation. In this survey, respondents were asked to select one of the three most desirable conjoint cards chosen at random from a set of nine cards, and this process was repeated seven times to obtain response results. The attributes of the conjoint analysis are "method of awarding points" and "amount of points awarded," "frequency of use of collection box locations," and "location of collection box locations. The levels of "how points are awarded" were "points that can be used at collection stores," "donations to social support organizations," and "points that can be used on social networking sites. The amount of points awarded was set at 1 JPY, 5 JPY, and 10 JPY per unit. The levels of "frequency of use of collection box locations" are "frequently used," "occasionally used," and "not usually used. The levels of "collection box location" were "supermarket," "drugstore," and "civic center.

The results of the conjoint analysis showed that the "store points" in the "granting method" category had the most positive utility. The next most practical is "Frequently used stores" under "Frequency of use of collection box locations". By attribute, "method of granting" was the most important, while "amount of grant" was the least important. In order to encourage consumers to participate in collections, it was found to be important to conduct collections at stores with high frequency of use. In addition, a system that rewards collection participants with points that can be used at the store would also be effective.

This study used conjoint analysis for resource recovery systems to understand consumer preferences for resource recovery. We plan to analyze the impact of different collection systems on resource recovery. We also intend to analyze the differences between core and light groups. Beyond that, we believe it is also important to understand changes in the attitudes of collection participants.

How to improve efficiency of coupled crop-livestock farming system?

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Qian Zhang [1] ***, Zhongxiao Sun*** [1]

1. *College of Land Science and Technology, China Agricultural University, Beijing, China*

Crop plantation and livestock production has decoupled with the development of chemical fertilizers and industrial livestock farming in recent several decades. However, decoupled production of crops and livestock has caused serious environmental impacts. Therefore, coupled crop-livestock farms, as one of agricultural transformation and circular economic development pathways, has re-caught more and more attention to mitigate environmental impacts. Nevertheless, it is still a challenge to compare the production efficiency of specialized farms with the coupled ones. A cutting-edge approach—cross-frontier analysis based on Data Envelopment Analysis (DEA)—therefore was applied to solve the problem in this empirical study. In 2021, we performed a questionnaire survey in Fengning Manzu Autonomous County, China, and collected 383 valid questionnaires data of agricultural cost and benefit from individual plantation and livestock farms in 56 villages, and 12 towns. The county is experiencing a transitional period of coupling crop and livestock production. The results showed that coupled crop-livestock farms were superior to specialized farms in terms of input savings. The reason might be the coupled farms are larger in size compared to the specialized farms in our samples. The results are consistent with the previous studies that proved that larger-size coupled farms are more efficient. In addition, we put forward to establish transition hubs to accelerate the coupling of crop and livestock farms in the future. This empirical study can shed light on sustainable agricultural planning in the specific county in China, as well as the other region around the world with similar issues.

Key words: coupled crop-livestock farm, efficiency, cross-frontier analysis, DEA, China

Value chains and process-based modelling of Li-ion batteries production and their environmental impacts

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Lorenzo Usai [1], ***Nelson Bunyui Manjong*** [1], ***Daniel Perez Clos*** [1], ***Sina Orangi*** [1], ***Anders Hammer Strømman*** [1]

1. NTNU

Abstract belonging to a proposed special session named: Securing raw materials supply for electric vehicles

Li-ion batteries are considered a key technology for the decarbonization of the transport sector, and in the Life Cycle Assessment (LCA) field there has been a significant number of studies that aimed at assessing the environmental impacts stemming from the production of battery packs for electric vehicles. Previous studies have found that approximately 50% of the global warming potential impacts, measured in kg CO2-eq., of producing a battery are due to the carbon footprint of the energy carriers, while the remaining 50% of the impacts is embodied in a few materials used for producing the batteries, i.e. Lithium, Copper, Aluminium, Cobalt, Nickel and Graphite. Regarding the energy use in manufacturing, most of these studies rely on either assumptions or on the very limited amount of primary data that has been made available in literature or reports. In addition, for the estimation of the environmental impacts generated by the value chains of key battery raw materials these studies rely on common LCA databases. These databases provided limited flexibility concerning the conditions in which the materials are extracted and further processed, meaning that the insights on the environmental impacts are somewhat uncertain and limited.

However, it remains unclear which stages in the materials extraction and production are the most environmentally detrimental, and there are only a few papers that investigate what key parameters drive such impacts. Understanding how and where the impacts are generated along the value chains of these raw materials can help in identifying the most impactful actions to reduce the upstream impacts of batteries. In addition, the battery technology is in continuous development; current state-of-the-art chemistries are being further optimized in formulation, and novel battery chemistries with theoretically better performances are being developed.

This work aims at performing cradle-to-grave LCAs of current and likely future battery chemistries for electric vehicles applications. To increase the robustness of the analysis, we aim at using a parametric value chains model that can provide insights into the upstream impacts of key battery raw materials. The use of this model can also help understanding whether future battery chemistries can lead to problem-shifting and the work can be used as a tool for an early identification of the likely hotspots of emissions.

In addition, to further strengthen the evaluation, we will couple the value chains model with a process-based production model that simulates the conditions of a battery production facility, and that can provide robust information regarding the energy use in all the manufacturing steps.

The scope of this analysis is therefore two-fold. First, we aim at reducing the uncertainty of the current production impacts of common Li-ion traction batteries via the coupling of a parametric value chains model with a process-based production model, and second we investigate potential chemistries that could be deployed in the future and investigate whether there are any trade-offs and potential hotspots of emissions that may require early interventions.

Future material demand for electrification of the UK Light Duty Vehicle Fleet

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ben Davies [1]

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The transport sector in the UK is set to follow a policy of widespread electrification. Stated targets are to ban the sale of all new internal combustion engine (ICE) cars by 2030, transitioning to a market dominated by battery electric vehicles (BEVs). In this form, the UK light duty vehicle (LDV) fleet can capitalise on a future national supply of low-carbon electricity. In isolation, this gives great potential to mitigate emissions from the use-phase of car ownership; in a life cycle context, this policy should be interrogated against considerations for material sustainability and global environmental impact.

The transition to electric transportation will necessitate the production of many lithium-ion batteries (LIB). A previous study has evaluated the future of LIB manufacture with potential routes to decarbonisation. Analysis finds that the environmental implications of modern vehicle-battery production is dominated by mineral processing; lithium, nickel, manganese, and cobalt are important critical resources, with limited geographical accessibility and ever-growing demand. Cobalt is of particular concern for the NMC-type batteries – market-leading in the UK fleet – and manufacturers are pursuing novel chemistries requiring smaller amounts of this mineral. The alternative LFP chemistry is also in consideration for BEVs, with much lower critical resource requirement.

LIB recycling is therefore an essential part of the future supply chain, offering more local and sustainable material availability. There are parallel policy targets in the UK manufacturing sector to invest in a national battery recycling ecosystem alongside the electrification of the transport sector. The goal is to close-the-loop in vehicle-battery end-of-life management; recover the critical materials and return them to the manufacture of new BEVs. Pyrometallurgical, hydrometallurgical, and direct recycling processing can be used to selectively recover battery materials from the waste stream. Efficient utilisation of resources already within the UK vehicle fleet will reduce demand for future primary supply.

This study presents a life cycle simulation of the UK LDV fleet, from present day through 2050. Modelling scenarios follow the electrification policy under different levels of grid decarbonisation, as well as a perspective for the outcome if the targets are missed. The authors examine the great demand for critical battery minerals and BEV manufacture, potential mix of battery chemistries, and the role of recycling in providing a sustainable secondary material supply.

The given target for electrification is ambitious, and sectoral GHG emissions are predicted to increase in the short-term before the technological benefits are realised. The near-zero transportation emissions can only be realised with strong decarbonisation of the electrical grid. The supply of critical battery materials presents a risk, with dependence on supply-chains across the globe. Recycling BEVs at end-of-life is an essential process to improve sustainability of production, as well as provide opportunities for further emissions reduction.

The Effect of City-Level Circular Economic Strategies on Reducing Carbon Footprints: A Case Study of Seoul

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Minji Yoon [1], ***Jong Ho Hong*** [2]

1. *Independent Scholar,* ***2.*** *Seoul National University*

In an economically globalised world with entangled supply chain networks, it is common for populations in urban areas, which are major consumption nodes, to meet their needs by consuming goods and services produced in the global hinterland beyond their territories. Therefore, it is important for urban climate change mitigation policies to consider the greenhouse gas (GHG) emissions that are embedded in the supply chain from a consumption-based perspective (i.e., carbon footprints) for effective global mitigation. Given the circular economy's aim to reduce pressures, preserve values, and regenerate the socio-ecological system by intervening throughout the entire supply chain process, from extraction to disposal, it represents one approach that urban areas can use to mitigate their carbon footprint. Despite previous assessments of the circular economy's potential to reduce GHG emissions and its effects on urban carbon footprint, numerical research on its impact remains insufficient.

This study examined urban carbon footprints, quantitatively analysed the effect of the circular economy strategy, and suggested ways to enhance urban climate change mitigation. It used an environmentally extended multi-regional input-output analysis to examine the city-level carbon footprints and carbon reduction potential in Seoul, a consumption-oriented metropolis with the smallest industry-sector GHG emissions of all the regions in Korea. It used three scenarios— business-as-usual (BAU), the 2050 Seoul Climate Action Plan (CAP2050), and circular economy (CE)—to identify the effects of circular economy strategies. BAU shows the baseline without any intervention. CAP2050 represents the situation if Seoul's current policy were fully implemented. CE depicts the result if Seoul added CE strategies encompassing decreased consumption and improved material resources and energy efficiency.

The first finding is that consumption-based GHG emissions in Seoul are 5.07 times larger than those of the production-based approach, the most significant ratio of similar studies. The second finding is that hotspots—housing and infrastructure, nutrition, and mobility—comprise about 90% of Seoul's carbon footprint and that Seoul depends on other regions for its needs. The third finding is that despite these material resources, such as steel, cement, and the nutrition sectors contributing to 9.15% of the total carbon footprint, the current accounting approach and climate mitigation policy implemented by Seoul neglect to address them, highlighting a significant policy gap. The fourth finding is that the CE scenario has significant carbon footprint reduction effects in Seoul, reducing 20% of the baseline emissions.

In conclusion, this study identifies the need for further research into the circular economy's impact on GHG emissions. While the results show that the implementation of circular economy strategies can lead to significant reductions in GHG emissions, there are limitations to the analytical method used and more empirical research is needed to understand the lead time of circular economy initiatives. The study also highlights the importance of developing more accurate and detailed databases. Finally, it is necessary to explore more multifaceted circular economy strategies to offset baseline emissions fully.

Raw material provisions and recycling of Lithium-ion Batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Shannon Davies [1]***, Volker Pickert*** [1]***, Farouk Tedjar*** [2]***, Oliver Heidrich*** [3]

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Electric Vehicles (EVs) powered by lithium-ion batteries (LIB) have emerged as the most popular replacement for petrol- and diesel-powered vehicles, inevitably leading to an increase in raw material demands and subsequent waste streams [1]. The value of materials within LIBs and the expected volume of the emerging waste stream means it is vital that LIBs are effectively and safely recycled in one of two ways. Open-loop recycling, also known as downcycling, means materials recovered from the recycling process are recycled into a different, lower quality product. Closed-loop recycling, considered the best-case scenario, is when materials recovered from the recycling process are in the correct chemical form and sufficient purity levels to be used in the same application of product [2].

Three recycling routes are most common for LIBs, i.e. pyrometallurgical, hydrometallurgical and direct recycling [2]. The pyrometallurgical process uses high temperatures to facilitate the reactions by which transition metals are reduced from oxides to metals and recovered in a mixed metal alloy [3]. The hydrometallurgical process uses aqueous solutions to dissolve the ions out of the cathode into a mixture in a solution [3]. In direct recycling, the cells must be shredded, and the black mass produced from this is then separated using physical processes, recovering the materials without causing chemical changes [3]. The earliest commercial process for recycling LIBs was a hydrometallurgical process by RECUPYL in 2005, which is now TES [4].

This presentation focuses on the hydrometallurgical process which produces high purity of recovered metals and uses low energy and low gas emissions compared to the other recycling processes [5]. The LIB is shredded under inert atmospheric conditions followed by vacuum drying and condensation [6]. The organic solvent from the electrolyte is recovered, whilst residual fluorine and phosphorus are removed in purification. Beginning the process like this means only clean air is released, rather than CO_2.

By investigating the hydrometallurgical recycling process, opportunities and problems that come with recycling are reported, including the safety of recycling, for example fires and how to prevent them. The investigation of this also reveals a range of recycling limitations. Despite partial operation, the primary limitation of LIB recycling is that complete closed-loop recycling of all materials, including the anode, cathode, electrolyte and separator, does not exist [7]. This is due to the waste treatments, namely shredding, involving some degree of material intermixing and small-scale dispersion of metals into those recovered in bulk. This overall reduction in the material quality prevents the use of the material for the same purpose, although full closed-loop recycling is not a utopistic future [8]. Secondly, safety in storage, transportation, dismantling, shredding and processing of LIBs is of high importance. This is a concern as the energy density in the compacted area of a LIB can result in a sizeable explosion [9]. The third limitation is that the industry has not developed the processing, reuse or recycling infrastructure to deal with the forecasted LIB waste stream [10]. This goes hand-in-hand with the lack of understanding that is needed to facilitate appropriate collection and processing of LIBs. The presentation concludes by highlighting the need for internationally agreed recycling infrastructure, not unlike the Basel Convention, to ensure economic, safe and socially responsible LIB recycling for both Open- and Closed-loop recycling technologies and infrastructure systems [11].

Reviewing life cycle assessments of carbon capture and utilisation - unclear goals lead to unclear results

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Carbon dioxide capture and utilisation (CCU) is the process of capturing carbon dioxide and using it to produce a product. It is a potential strategy for mitigating greenhouse gas emissions and replacing fossil feedstock in chemical production. Life cycle assessment (LCA) is important to assess the carbon reduction capability and is often used to evaluate the environmental impacts of CCU processes. This study aims to analyse the methodological choices made in life cycle assessments of carbon capture and utilisation systems, and identify and evaluate the logics of the modelling in the studies.

LCA studies of CCU processes were found through a systematic search and reviewed regarding LCA methods. The collected articles were coded on different aspects (e.g. goal, system boundaries, impact assessment) and a framework was developed to describe the different scopes the CCU systems are modelled from in the assessments.

106 articles were reviewed, published between the years 2002 and 2021. 88 of them evaluate products produced through a CCU route and make a comparison to the existing conventional way. Thus many aim to do the same kind of assessment, but results from the review show that the scope differs, and the majority do not clearly state their goal with the LCA. There is likely an aim of the study which could include a reason for using LCA, but the goal of the LCA (as in goal and scope definition) is often not found in the article.

It was also found that the system boundaries stated in the body of literature are often “cradle-to-gate”. The cradle can however be set to different points in the system, and the scope of the studies varies a lot depending on where the cradle starts and what is included in the assessment. In the case of CCU, it is found that the cradle can be at the process the flue gases are captured from (38 cases), the capture process (44) or at the CO2 conversion process (24).

The justification for not including the whole life cycle of the product (only 19 are to the “grave”) can be that the product has the same use and end of life as the product it is compared to, often the conventional alternative. However, only including part of the system in the analysis can give misleading results when the emissions can be presented as negative in the shorter perspective due to the temporary storage of carbon in the product. A longer time perspective and different system boundaries are needed to see if the carbon in the product is emitted or not shortly after leaving the factory gate.

Given that CCU processes are often emerging technologies, the purpose and context of the study matter for how the results can be used, but the goal of existing life cycle assessments seldom handles these aspects. The LCA results are often used for comparison with conventional technologies or for comparing the CCU product to an existing product, although not always reflected in the goal. With underdefined goals, different system boundaries and varying methods for accounting, understanding assessments of CCU becomes confusing. This highlights the need for methodological guidelines and clearer goal definitions in life cycle assessments of CCU to ensure meaningful and consistent evaluation of the environmental impacts and potential of these emerging technologies.

Understanding resilience of urban food-energy-water system: Insights from the Beijing Megacity

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Xinqing Li [1], ***Lixiao Zhang*** [1], ***Yan Hao*** [1], ***Zhimin Shi*** [1], ***Pengpeng Zhang*** [2], ***Xin Xiong*** [1], ***Yuqin Li*** [1], ***Zhongming Lu*** [3]

1. *Beijing Normal University,* ***2.*** *Hebei Normal University,* ***3.*** *The Hong Kong University of Science and Technology*

Lessons from the increasing resource crisis of food-energy-water (FEW) force cities to strengthen resilience building holistically. To better understand and promote the improvement of urban resilience, an integrated quantitative lens of the metabolic regime is required. Based on a multi-node and multi-process research framework, an ecological network model was developed to explore structural and functional characteristics of urban FEW metabolic system, with consideration of local availability, cross-region supply and resource nexus. This model was demonstrated through application to the Beijing Metropolis. Results reveal the heterogeneity of urban FEW network's organizations and system-level properties. There are 0.48 million tons of food (indicated by nitrogen), 3300 billion mega-joule of energy and 8.6 billion cubic meters of water metabolizing within the city boundary, respectively in the chain-type, tree-form, and composite network structure. Upstream production and processing sectors mainly play the role of pulling overall network development, while downstream service industry and domestic living nodes, and the terminal stages as wastewater and solid-waste treatment display more driving forces. Water network, with more positive relationships between nodes and greater circulation level of flows, has the higher stability index (1.85), while energy network performs poorly due to a lack of redundancy and food network is more sensitive to external changes. These findings provide valuable insights to guide megalopolitan resilience improvement, such as reinforcing cross-regional cooperation, strengthening local resource reserves, enhancing utilization efficiency of dominant industries, and promoting treatment and reuse.

Demand and deployment of hydrogen liquefaction plants in Europe

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:28: Transitions (short presentations) (B0.41 KOG)

Alicia Torres Gomez [1], ***Graham Pullan*** [1]

1. University of Cambridge

The global hydrogen demand is predicted to rise to 425-650MtH2/year by 2050, which is 6-9 times the current pure hydrogen demand [1]. In particular, the liquefied hydrogen (LH2) demand is projected to be of 42MtH2/year for aviation [2] and 2-9MtH2/year for marine applications by 2050 [3,4,5]. Hydrogen international trade, much of which is expected to be in liquefied form, is forecast to reach $100-300 billion by 2050 (1000 times increase) [6].

State-of-the-art hydrogen liquefaction plants are based on simple low-efficiency Claude cycles with Nitrogen pre-cooling (Specific Energy Consumption (SEC) of 10.8-12.7kWh/kgLH2) [7,8]. Current European hydrogen liquefaction capacity is less than 30 tonnes per day (tpd) in total over 4 sites (France: 1, Netherlands: 1, Germany: 2) [9,10].

This research first quantifies the European LH2 demand by 2050. Then, the scale and efficiency of future plants is investigated. Hence, the number of liquefaction plants required over 14 European countries is forecast. Finally, the renewables capacity required is compared to achievable limits.

The overall energy system of 14 European countries is analysed using the EnergyPLAN software [11] and data from the EU Heat Roadmap Europe (HRE) project [12,13]. This project has two scenarios, business-as-usual (BAU2050) and ambitious (HRE2050), for 14 countries which are representative of the EU (90% of the population [14]).

The total hydrogen demand for Europe is of 200TWh/yr in the BAU2050 scenario and 2,600TWh/yr in the HRE2050 scenario. The electrolyser capacities required are 44 TW and 630 TW respectively. The spread of hydrogen demand and electrolyser capacities across Europe is shown cartographically. If a 100 MW electrolyser capacity corresponds to 48tpd of hydrogen [15] and 10% of all hydrogen produced is liquefied [16], the European liquefaction capacity required is 2,000tpd and 30,000tpd in the two scenarios respectively (66-1000 times the current capacity).

Current state-of-the-art plants each have a capacity <35tpd (<10tpd in Europe). However, as the LH2 demand rises, newly built plants will need larger capacity. Future plants are expected to be >50tpd, with some over 200tpd. This increase in plant scale shifts the economics from minimising CAPEX to OPEX and allows the introduction of more efficient components and processes (e.g. mixed refrigerant pre-cooling, Helium-Neon Joule-Brayton cooling, use of turbo-compressors, etc.). Therefore, plant efficiencies are expected to double from about 25% (SEC=13 kWh/kgLH2) to 50% (SEC=6.5 kWh/kgLH2) [10,17].

Based on a future average plant capacity of 100tpd, a map of the number of liquefaction plants required by country for each scenario was created. In total, 20-25 plants will be required in the BAU2050 scenario and about 300 in the ambitious scenario. In the BAU2050 case, only 3 countries need more than one 100tpd plant. In the HRE2050 scenario, the countries with the largest plant deployment will be Spain (51), UK (49), France (46) and Germany (42).

Finally, the HRE2050 renewables deployment needed is 1,200TW of wind and 250TW of solar. Maps showing the predicted deployment versus the achievable wind and solar capacities [18] for the 14 countries show that the solar capacity is realistic for all but four countries, but the wind capacity is unrealistic in most countries.

In summary, 20-300 hydrogen liquefaction plants of large capacity (~100tpd) and high efficiency (~50%) will need to be deployed by 2050 to meet the fast-rising demand of LH2 in Europe. The renewables deployment needed for this decarbonised scenario may prove challenging.

Accounting of Greenhouse Gas Emissions in China's Electricity Generation and Consumption

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ruoxi Xiong [1], ***Ming Xu*** [1]

1. *School of environment, Tsinghua University*

The power sector is the largest contributor to China's carbon emissions, accounting for 41% in 2019. In order to meet the Dual Carbon Goals, reducing emissions from the power industry is a priority. In China, the power grid separation of generation and consumption creates complexity in calculating GHG emissions. The shift towards clean energy sources has changed the energy mix and highlights the need for updated carbon emission factors. Regional differences in energy structure and electricity trade also result in diverse carbon emission factors.

To address these challenges, this study aims to calculate direct carbon emission factors at both the production and consumption ends using the latest data from 2020 or 2021. The IPCC guidelines and the Quasi-Input-Output model will be used to calculate carbon emissions in six power grid regions and provinces in China. This study will serve as a foundation for the creation of a life cycle assessment inventory database for the power industry. The comparison of production and consumption carbon emission factors will also provide insight into the division of emissions reduction responsibilities among regions.

Understanding Interconnection in Resilient Multimodal Public Transportation Networks: A Case Study from Hong Kong

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Zizhen Xu [1] ***, Shauhrat Chopra*** [1]

1. City University of Hong Kong

Transportation is one of the critical urban infrastructures, and our dependence on it persists as cities sprawl. Interconnection favoring mobility is where local policy efforts continue, whereas its impact on resilience is poorly understood. There are growing concerns about the resilience of transportation systems to the threat of climate disasters and social unrest. Current research on public transport resilience focuses on single-modal public transportation networks (PTNs) or simple aggregations of multiple networks through transport complexes. To gain a comprehensive understanding of multimodal public transportation networks (MPTNs), a systematic approach is needed to consider network interconnections in a geospatial manner. From a topological perspective, MPTN may behave differently compared to single-mode PTN. To explore how it topologically affects network resilience, this research adopts a real case study in Hong Kong and reveals the advantages of MPTN.

The study models six modes of PTNs in Space-L representation, including metro, light rail, franchised bus, public light bus, ferry, and tram, and there are a total of 8,644 nodes and 15,551 edges. The MPTN is created subject to proximity, and the haversine distance between nodes is computed to determine where to add additional intermodal edges. In the proximity analysis, the distance limit to identify intermodal edges is considered a variable, which may vary among cities and nations. Therefore, we analyze a group of MPTNs created with distance limits from 0 to 1,600 meters and select 100 meters to show detailed results, as 100 meters is roughly the average size of *public transport interchange* sites in Hong Kong.

The six PTNs are integrated network-by-network in the analysis. We observe the change in network characteristics and resilience-related indicators, such as network efficiency, geospatial efficiency, preparedness indicator (node homogeneity), robustness indicator, and network interoperability (passenger relocation capability). Specifically, we introduce a null model as the benchmark for network properties like robustness that heavily depends on network size and the number of edges. The null model integrates the Erdos-Renyi model with additional geospatial constraints to avoid arbitrarily added long edges.

Results display that the MPTN has prominent topological advantages in efficiency and resilience-related indicators. Node homogeneity increases significantly, indicating better preparedness as the vulnerabilities are more distributed across the network. In terms of robustness, MPTN interestingly outperforms the benchmark, especially when facing degree-based attacks. It exhibits high fault tolerance to minor disturbances, which is not observed in the individual PTNs. Moreover, the distance limit analysis provides evidence that, for real-world applications, enhancing intermodal transfer brings significant marginal benefits at a short distance, and the cost is relatively low. Additionally, real-world MPTN has better efficiency and geospatial efficiency than the null model in this research.

Water loss and return flows matter for water stress mitigation in China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***Dan Wang* [1], *Reetik-Kumar Sahu* [2], *Taher Kahil* [2], *Ting Tang* [2], *Yuli Shan* [3], *Klaus Hubacek* [4]**

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Water is withdrawn, lost, consumed, polluted, returned, treated, and reused within the societal water cycle due to human activities, contributing to regional water stress. In this study, we aim to study impacts of the societal water cycle on water resources and explore strategies for reducing water stress in China. The results show that most provinces in China suffer from water quantity and quality stress. However, there is a significant potential to reduce water quantity stress by 36-79% with reducing water loss and return flows. Return flows especially from agriculture and households contribute the most to water quality stress in China. The top five sectors with the greatest potential to mitigate water stress are identified for each province, which could reduce total water stress in these provinces by 28-74%.

Improving the Modelling Framework for Terrestrial Acidification in Life Cycle Impact Assessment

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***Marion Lebrun* [1], *Francesca Verones* [1], *Andrew Henderson* [2]**

1. NTNU, 2. University of Texas at Austin

Terrestrial acidification is one of the many impact categories considered in Life Cycle Impact Assessment (LCIA) for impacts related to ecosystem quality. When emitted into the air from industrial plants, vehicle exhausts or agricultural practices, nitrogen oxides (NO_x), sulfur oxides (SO_x) and ammonia (NH_3) molecules undergo chemical reactions in the atmosphere. They form acidifying dissociation products that are then deposited on the Earth's surface and lower the soil's pH. Such phenomenon can lead to biomass decline, competitive exclusion by acid-tolerant species, changes in plant metabolism, and overall, altered biodiversity. Even though LCIA methods cover terrestrial acidification, there is a need for an up-to-date and consistent modelling framework to derive new spatially differentiated characterization factors with a global coverage.

Characterization factors (CFs) quantify acidifying emissions' contribution to terrestrial acidification and are the resulting combination of three elements. First, the atmospheric fate factor (FF) represents the atmospheric impact pathway with climatic conditions and deposition mechanisms, from an emission location of a certain pollutant to the corresponding deposition location. The FF calculations, resulting in a Source-Receptor Matrix, can be done using atmospheric chemistry models such as GEOS-Chem (Roy et al., 2012). Second, the soil sensitivity factor (SF) measures the receptor location's change in H^+ concentration over a certain area due to the deposition of the pollutant. Here, geochemical models such as PROFILE (Warfvinger and Sverdrup, 1992), MAGIC (Cosby et al., 1985) or WITCH (Goddéris et al., 2006) are considered to derive SFs. However, the last two models have not been used in that context. Finally, the effect factor (EF) evaluates the absence of species in the receptor location following a pH decline, using species sensitivity distributions.

We present a new, up-to-date modelling framework for regionalized characterization factors at endpoint level with global and more detailed spatial coverage. We include updated fate (integration of temporal variability), sensitivity, and effect (based on the work from Gade et al., 2021) factors. In order to make this LCIA method consistent with other approaches within in ecosystem quality, we will couple it with the Global Extinction Probability (Verones et al., 2022). This allows us to assess both impacts at regional scale, as well as global extinction. This update is thus an important step for improved and more consistent assessments across ecosystem quality.

Environment-Health performance of culinary patterns in traditional recipes across the China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

fengyin xiong [1], ***Gang Liu*** [1], ***Li Xue*** [2]

1. *University of Southern Denmark*, ***2.*** *China Agricultural University*

A growing concern of diet choice and shift recommendation has induced another increasing attention on the field of recipe, which is the primary source for the study of particular food culture and behavior. Internet-sourced recipe uploaded on the web reflect what the residents cook and how they cook it. Generally, the profusion of recipes has been served for accommodating their preferences adhere to their bond with tradition despite of the awareness to the importance of healthy lifestyle, where it is still unclear what types of ingredients exists from region-specific sits and how these factors (cooking technologies, time) are related to individuals' health and environment. especially when we stand on the verge of an epidemic of diet-linked disorders and urgently need to achieve sustainable development goals, Analysis of data pertaining to recipes by clarifying their linkage with both nutritional and environmental issues is expected to be a promising choice to achieve that the recommended recipes to be cooked most frequently exerts less environmental impact simultaneously with higher healthy benefits. With this motivation in mind, we set to investigate the way where dataset from well visited Chinese online recipe portals is acquired by web crawler, and exerted data cleaning for the structured compilation to decode mentioned food culture. We get the structured recipes repertoire comprising of meticulous integration of over 100k prevalent online recipe from eight regional culinary cuisines for next process. Specifically, we use network analysis based on the statistical ingredient information for further characterizing and distinguishing recipes from different regions. A qualitative framework on basis of food ingredients, environmental factors interlinking with nutrition profiles, is then developed to examine the role of factual personal health and environmental outcome. We integrate the three indicators (carbon footprint, nutrition balance index, nutrient-rich food index) into the two food-related fields of health and environment and condenses these three results into two easily communicable result presenting the overall performance of per serving in detail. Further upscaling of the eight cuisines, our results confirm the strong effects of geographical and cultural similarities on recipes, health, environment, and culinary preferences. The empirical results support the framework's intuition and showcase its ability to retrieve a healthier and environmentally friendly recipes.

Optimization of the Circulation Strategy of Plastic Waste based on the Life-cycle Consideration of Spatial Factors and Technologies of Recycling Plants

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Richao Cong [1], ***Atsushi Fujiyama*** [1], ***Toru Matsumoto*** [1]

1. *The University of Kitakyushu*

In recent years, increasing concerns about global ocean plastic waste (PW) problems and the issuance of the ban on importing PW by the Chinese government have accelerated the transition of PW recycling technology in relevant nations. Meanwhile, global nations have declared their net zero-emission goals by the middle of this century including Japan. In this study, we developed an optimal matching approach aiming to achieve the maximum reduction of carbon dioxide (CO_2) emissions from the whole lifecycle of industrial plastic waste (IPW).

At first, an optimization problem was designed as maximizing the total emission reductions by matching the amounts of IPW for relevant facilities. The total emission reductions included those from transportation, pre-treatment, recycling, and residue disposal processes compared with the alternative systems (evaluations on avoided products). The matching focused on detecting the optimal amounts of IPW transported to individual plants (as their geolocations and disposal capacities of plants) and recycled by different technologies (material recycling: MR, chemical recycling: CR, and energy recovery: ER). Then, relevant constraints were prepared. Finally, the solutions were solved by using a linear programming approach. Here, we provided details on methodology exploration by using the IPW data from Mie Prefecture, demonstrated for polyvinyl chloride waste (PVCW). To apply the proposed approach to a social problem, we designed two scenarios (the current scenario and future scenario) and quantified the additional mitigation potential of CO_2 emissions between them, of which the newly developed recycling techniques would be utilized.

As our optimal solution, the CO2 emission reduction intensity was increased from 2.9 t-CO_2 t^{-1} in the current scenario (2022 level) to 5.0 t-CO_2 t^{-1} in the future scenario (2024 level) which reflected a high mitigation potential by the newly developed recycling techniques. Parts of pretreatment facilities, all of MR facilities, and parts of CR facilities were allocated to dispose of the PVCW so as to meet the maximum emission reduction. The benefits from the optimization will be checked from environmental and economic aspects in the future.

Developing an Optimal Energy Supply System to Support the Regional Decarbonization: A Case Study from Kitakyushu City, Japan

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Richao Cong [1], Mirei Abe [1], Atsushi Fujiyama [1], Toru Matsumoto [1]

1. The University of Kitakyushu

In recent years, global nations have declared their net zero-emission goals by the middle of this century including Japan. There has been considered a large potential for emission mitigation from the energy supply industry as the development of renewable energy generation and storage technologies. To support regional decarbonization, this study focuses on designing an optimal energy supply system in which renewable energy (onshore, offshore wind power, solar power, and biomass power) are made as prioritized sources to meet the temporal energy demand. The optimization algorithm is used to detect the optimal supply amount for each energy source at an hourly level. It is demonstrated in an industrial city of Japan (Kitakyushu) from two aspects: carbon dioxide (CO_2) emissions and cost.

At first, the annual supply potential of renewable energy was estimated based on governmental databases and weather reports. Meanwhile, the annual energy demand was calculated based on emission intensity and statistics data. Then, the annual ones are disaggregated to an hourly level, considering the hourly, weekly, monthly, and seasonal patterns. The storage battery is introduced to the current system to rebalance the supply and demand sides. Through its control, the surplus of balance between renewable energy and demand will be stored by the battery without supplying from grid power. On the other hand, the grid power will be only supplied when the total of stored energy an hour before and renewable energy potential is less than the demand. The objective function is defined as the minimum CO_2 emission or cost including those from four types of renewable energy, grid power, and the usage of the storage battery. The constraints are considered as including the battery capacity, charging and discharging balance, hourly and annual supply potential for each type of energy, and hourly supply should exceed the demand.

As our solution, 99.9% of onshore wind power, 56.8% of offshore wind power, 69.8% of solar power, and 45.4% of biomass power were essential in a year to meet each hourly demand and achieve the minimum CO_2 emissions. From an economic aspect, only onshore wind power (79.7% of yearly total), solar power (70.4%), and grid power were detected as the optimal sources of energy supply to meet the demand.

Revealing and addressing the pesticide tradeoff of sustainable diets

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Xinhan Yin [1], ***Yi Yang*** [1], ***Jingcheng Yang*** [1], ***Peter Fantke*** [2]

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Current global agri-food systems have significant impacts on the environment, especially regarding greenhouse gas emissions, land and water use, and the threat to biodiversity. Moving toward sustainable plant-based diets has been widely suggested as an effective and promising solution to reduce environmental stresses. However, few studies have considered how sustainable dietary transition might affect crop pesticide use and associated ecotoxicity impacts. Pesticides are widely used globally to safeguard crop production by controlling the occurrence and spread of weeds, pests, and fungus. However, a large fraction of pesticides ends up in the environment after application, threatening the health of ecosystems. Here, we collected pesticide-crop data for 68 crops and 389 active ingredients in the US and estimated the pesticide usage and ecotoxicity impact of associated with five US diet styles, including one baseline diet (Current Diet) and four recommended styles (Healthy US Diet, Mediterranean Diet, Vegetarian Diet and the widely studied EAT-Lancet Diet). Our results reveal that given the same calorie intake (2500 kcal/person/day), the Current Diet has lower pesticide usage than all recommended diets but the EAT-Lancet Diet. Considering the freshwater ecotoxicity impact of different pesticides including their fate and transport in the environment, the Current Diet has the lowest impact, while Mediterranean Diet has the highest impact. These results are mainly owing to the high ecotoxicity of insecticides and fungicides heavily applied in vegetables and fruits production. The tradeoff, however, can be minimized by reducing the usage of some of the most toxic pesticides, e.g., those banned in the EU but still used in the US. Reducing food waste can also be helpful. Combining these two measures can lower the pesticide freshwater toxicity impact of recommended diets close to or below that of the Current Diet. Our study reveals an important tradeoff associated with sustainable diets and proposes ways to address the tradeoff, making those sustainable diets even more sustainable.

Capturing “More-good” and “less bad” social impacts: the methodology revealed

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Pasan Dunuwila [1], ***Ichiro Daigo*** [1], ***V.H.L. Rodrigo*** [2], ***Hiroki Hatayama*** [3], ***Koichi Shobatake*** [4], ***Kiyotaka Tahara*** [3], ***Takeo Hoshino*** [1]

1. The University of Tokyo, 2. Rubber Research Institute, 3. National Institute of Advanced Industrial Science and Technology, 4. TCO2 Co.,Ltd

Social Life Cycle Assessment (LCA) is a methodology used to assess the social impacts of a product, process, or service throughout its life cycle. Social LCA lacks a designated framework. The UNEP/SETAC code of practice, released in 2009 and updated in 2020, acts as the main framework for SLCA. It defines six stakeholders (i.e., workers, local community, society, children, value chain actors, and customers) who are impacted by a product, 40 subcategories (social themes, such as child labor), and many indicators for determining the scale of that impact. Many SLCA methodologies focus on the negative social impacts and reductions, while positive social impacts and their increments have been given less consideration. Positive social impacts highlight chances for improving human well-being and present a comprehensive picture of a product’s overall social impact. Despite some attempts to evaluate the positive social aspects of products using various methodologies and norms by previous studies, no straightforward methodology exists to distinguish between the positive and negative social impacts of a product. In addition, the existing studies could only assess the current social condition of the product and could not measure any changes in positive social impacts after improvement. Both are necessary for correct decision-making using SLCA. To fill the existing gaps, we introduce a new SLCA methodology that can distinguish between the positive and negative impacts of subcategories in the latest version of the UNEP/SETAC SLCA code of practice. We distinguish between positive and negative impacts by deploying a sufficiency level called basic requirement. The basic requirement is the criterion that should be established to avoid social issues of each subcategory. These basic requirements are defined per organizational standards (e.g., ILO guidelines), international or local agreements, UNEP/SETAC SLCA guidelines, and other relevant literature. We term ‘more good’ if positive impacts are improved and ‘less bad’ if the negative impacts are reduced with an improvement. Social impacts were evaluated using the social performance index (SPI) computed by multiplying social performance levels with worker hours at the factory/company level. Social performance levels are evaluated using a decision tree and a systematically proposed set of indicators representing basic requirements and positive and negative domains of each subcategory. Worker hours were used as an activity variable enabling aggregating individual SPIs across a product’s entire supply chain and are evaluated using a worker hour model. This methodology assists in refining the supply chain of a product (pinpoints social hotspots) or helps compare the social well-being of products. As the next step, we will conduct a case study to see the functionality of the suggested methodology.

Food waste-Energy-Water-Emissions (FEWE) Nexus in the Food Service Sector: Comparative Life Cycle Assessment of Locally Produced vs Imported Meal

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Paschal Milindi [1]***, Francesco De Lieto*** [1]***, Shauhrat Chopra*** [1]

1. *City University of Hong Kong*

The food waste, energy, water, and emission (FEWE) nexus in the food service sector (FSS) should be analyzed in order to ensure proper procurement and management of materials and energy flows to minimize environmental impacts from food systems. Life cycle assessment (LCA) is the method applied to analyze the amount of energy use, water consumption, and emission along the food supply chain (FSC). The FSC stages include all activities from agricultural production to consumption. In this study, the inventory of imported food ingredients and energy flows from pasta meal cooking at commercial kitchens in Hong Kong were audited and then processed by SimaPro software. A similar process was repeated for the pasta cooked in Australia and then shipped to Hong Kong as a ready-to-eat meal. The pasta ingredients were unsalted butter, cheese, wheat flour, eggs, fresh truffles, and salt. When a comparative LCA is performed, the amount of carbon footprint, energy footprint, and water footprint per meal portion are determined. Furthermore, food waste produced along the FSC is analyzed using the FAO-developed methodology in which the food waste is the function of the quantity of food available at each stage along the food supply chain, food wastage percentages, conversion factors, and allocation factors. The results discussed the FEWE nexus trade-offs among the impact results along the FSC for both cases. The results show that the ART meal's indirect global warming potential (GWP) causes higher carbon emissions than the LMO meal. Also, the direct CED of the ART meal is higher than that of the LMO meal. The direct WC of the ART and LMO do not differ. Furthermore, the indirect ART food waste (FW) is less than the LMO one, while direct FW for both ART and LMO meals is negligible. The study concluded that cooking meals in Hong Kong using imported ingredients results in better environmental performance than importing ready-to-eat meals.

Linking resource circulation of plastics with the industry-wide decarbonization through life cycle thinking

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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1. The University of Tokyo; National Institute for Environmental Studies, Japan

Towards realization of the carbon neutral society, decarbonization is nowadays one of the most concerned issues in any industry. At the same time, being led by the EU circular economy policies, resource circulation including recycling also draws much attention worldwide. Decarbonization and resource circulation have often been discussed independently, while it is sometimes postulated that an advance in resource circulation (unconditionally) contributes to decarbonization of the plastic supply chain. However, such a positive relationship is not necessarily self-evident and needs to be carefully examined from the life cycle perspective.

The chemical industry is a major contributor to the greenhouse gas emissions in many industrialized countries. Moreover, the chemical industry is not only responsible for the direct process emissions but for emissions from other stages of the life cycle of its products. Resource circulation of plastics is specifically relevant to decarbonization of the chemical industry, and a lot of chemical makers in the world are recently devoted to developing chemical recycling processes of waste plastics.

On the other hand, utilization of waste plastics is also regarded as one of the key options towards decarbonization in other industries in Japan. For example, the steel industry, which is also a major contributor to the greenhouse gas emissions, has been utilizing the significant amount of plastic packaging waste in the steelmaking processes as a substitute of coal that is used as a raw material for coke ovens and reductant in blast furnaces.

In the meanwhile, chemical makers are also searching for other carbon-neutral feedstock options including biomass, carbon recycling, and direct air capture technologies. Similarly, steelmakers are developing technologies which could realize the carbon neutrality in their steelmaking processes, such as hydrogen-based reduction and advanced electric furnace technologies. Such a situation is also true for the cement industry, which is another major greenhouse gas source. Cement makers have been utilizing waste plastics as a fuel for clinkers to replace coal, whereas other alternative fuels including ammonia and hydrogen are also examined recently. Therefore, the demand for feedstock recycling and energy recovery of waste plastics depends on whether and how much other decarbonization options in the relevant industries could be implemented in the future.

According to the EU circular economy principle, mechanical recycling is given priority over chemical or feedstock recycling, which is regarded as an outer loop. Energy recovery and feedstock recycling options outside the plastic supply chain are considered to be included in the linear economy. So far, many life cycle assessment studies in Japan have shown that feedstock recycling in the steelmaking processes and/or high-efficiency energy recovery are potentially effective for reducing the climate change impacts, often rather than mechanical recycling. However, the results can be changed when we assume the future situation in which decarbonization technologies are put into practice in the relevant industries.

In this presentation, taking the above-described complexity into consideration, the linkage between the resource circulation of plastics and the industry-wide decarbonization is discussed through life cycle thinking. Firstly, importance of the future projection for external conditions including the feasibility of carbon-neutral electricity and hydrogen procurement, as well as the capacity of carbon capture, utilization and storage, is pointed out. Then, a vision for the plastic resource circulation that harmonized with the decarbonization strategies of various industries is presented.

Could solar PV adoption in rural Africa catalyse charcoal production – an examination of rural Zambia

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hillary Chanda [1], ***Eugene Mohareb*** [1], ***Michael Peters*** [1]

1. University of Reading

Energy access remains a persistent challenge in developing regions globally. In Sub-Saharan Africa (SSA), off-grid solar technology represents a transformative technology in the context of an underdeveloped electricity infrastructure (Mohammed Wazed *et al.*, 2018). In 2018, SSA had 915 million people, 68% of whom had no access to electricity (Okoye and Oranekwu-Okoye, 2018). Many of these are reliant on biomass to provide basic domestic energy services, often in the form of charcoal. Indoor charcoal use degrades indoor air quality, while also leading to unregulated timber harvesting in a region that is being afflicted by persistent droughts exacerbated by climate change. Africa, especially SSA, has the lowest electrification rate in the world and this has mainly been due to demand side constraints (Blimpo, Postepska and Xu, 2020); with rural people living at less than \$1.5/day, it is a challenge to supply electricity at a cost reflective tariff (Mugisha *et al.*, 2021). The weak purchasing power of the rural population has made it difficult to implement PV projects to date (Vanadzina *et al.*, 2019). However, SSA receives some of the highest solar insolation levels on Earth, ranging from 4 to 7 kWh/m^2/day (Cozzi *et al.*, 2020). Coupled with declining PV costs and improving energy conversion efficiency, PV is becoming a cost-effective solution and alternative to national grid extension (Winklmaier and Bazan Santos, 2018).

This study aims to identify challenges and opportunities relating to the effective design, adoption, and delivery of solar PV services for remote rural communities in Zambia in SSA. It explores which energy services are most important in rural Zambian communities, across a range of domestic and commercial options. Over 120 rural subsistence farmers were included in data collection, along with commercial farmers. Interviews and focus groups were used for primary data. A conceptual framework combining two theoretical frameworks: theory of planned behaviour and diffusion of innovations, was used.

Results seem to indicate a relationship between adoption of PV in remote rural areas and increase in small-scale charcoal production. Research participants indicated that increased charcoal could be used to finance their desire to own adequate solar PV systems. Due to the high prices of farming inputs, fertilizer dependent soil, and poor rainfall, some farmers have resorted to increased charcoal production to raise funds to survive and finance solar PV systems. Further, the farmers revealed that their biggest market was in urban areas as most rural people rely on unpyrolysed firewood for energy. Urban charcoal demand is further fueled by increased power rationing due to drought-affected hydropower stations.

Tracing nitrogen flows associated with beef supply chains in the United States: a consumption-based perspective

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Anaís Ostroski [1], ***Oleg A. Prokopyev*** [1], ***Vikas Khanna*** [1]

***1.** University of Pittsburgh*

Food supply chains have become increasingly complex and characterized by great distances between production and consumption. Highly connected value chains are beneficial due to resiliency and protection against disruptions, but they lack traceability and transparency. Further, the impacts of food consumption often occur in far and distant production locations. Tracking product flows along value chains is especially important to quantify and assess environmental burdens that are local in nature, such as nitrogen pollution. Losses of reactive nitrogen in the environment have been linked to decrease in water quality and loss of biodiversity. Modern agriculture has become a major driver of alterations in nitrogen cycle. More specifically, production of protein-rich foods has been shown to significantly contribute to increases in anthropogenic nitrogen inputs. In particular, beef production is resource-intensive and requires large amounts of animal feed produced from crops that are dependent on “new nitrogen” from synthetic fertilizers and bio-fixation. In addition, nitrogen excretion in manure is also an important source of reactive nitrogen. Although there is a rich body of work on nutrient footprint for beef production, there is a gap in the literature regarding the spatial distribution of nitrogen losses throughout the supply chain. Additionally, most studies focus on production-related impacts making it difficult to understand the impacts of consumption that is spatially disconnected from the point of production. Consumption-based accounting can be used to complement traditional footprints, as quantifying both the origin and destination of food flows is critical for capturing underlying drivers, hotspots, and overall sustainability of food systems.

Using publicly available data and an optimization-based framework, we model beef supply chain networks at the county level in the United States and assess their associated nitrogen flows. We couple nitrogen budgeting and consumption-based accounting to trace the link between nitrogen emissions and consumption. Specifically, we construct a weighted network of nutrient flows based on the calculation of nutrient mass balance, including synthetic fertilizers, manure production and crop uptake and residues. Reactive nitrogen releases, including ammonia, nitrous oxide and nitrates, are quantified at every step of the supply chain from feed production to animal farming to consumption. The resulting network model aids in tracing back the amount and location of nitrogen releases caused by beef consumption of each county. Results suggest that beef consumption has a low nitrogen efficiency, with most of the nitrogen losses occurring at the animal farm stage. Production practices, such as average animal weight, diet, and manure management influence the total nitrogen surface loss. One year worth of beef consumption in the United States is associated to approximately 1.65 Tg Nitrogen emitted to the environment, most in form of diffuse pollution during feed production phase. Nitrogen losses are highly skewed and occur more intensely in a few key counties in the northern and southern plains, because a small number of counties are responsible for most of cattle feeding and slaughtering. This also causes a large inflow of young cattle and feed towards these regions and highlights the importance of understanding the spatial heterogeneity of nutrient footprints. Furthermore, beef consumption in a single county is associated with nitrogen losses in over 200 counties on average. Implications of these findings for the quantification of nitrogen footprints of animal-based products, as well as for policymaking and consumer food choices will be discussed.

Integration of chemical engineering models in waste management LCA: Case of composting

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Due to population growth, municipal waste management is increasingly becoming a major issue for local decision makers. Along with the evolution of legislation and policies, they must consider environmental impacts of their choice. Thus they are moving towards waste-to-resource treatments. To help guide decision makers towards an informed and environmentally sound choice, LCA tools strive to assess all relevant direct and indirect environmental impacts and benefits of waste treatment processes. Databases such as EcoInvent offer pre-established life cycle inventories of waste treatment processes as “black-box”, in which values of emissions to the environment and physico-chemical characteristics of co-products are defined in a fixed manner. These values are often taken from measurements on specific sites over a limited period, and correspond to treatment of a specific territory waste. Using these fixed coefficients to guide waste management policy essentially ignores the major influence of variabilities in waste composition on the environmental performance of treatment processes (Bisinella et al., 2017). Moreover, technological representativeness is still limited because these are simply average data of selected plants, and do not cover full range of possible technological variants. Other more advanced tools, such as Easetech, Swolf, and Orware, have partly lifted these limitions by integrating in their modelling transfer coefficients, which assume a linear relationship between waste composition and emissions (Clavreul et al., 2014; Dalemo et al., 1997; Levis et al., 2013). However, these transfer coefficients are empirically calculated for a certain set of conditions, and do not reflect complex physical and chemical processes that occur throughout the treatment. These limits increase uncertainties of LCA results and reduce our ability to confidently tailor processes to territory specificities. Through a case of composting, we try to integrate chemical engineering knowledge into LCA calculations to get as close as possible to real processes, and thereby reduce uncertainties. Indeed, in the literature, many models predict kinetics and emissions of composting processes, although these models were not designed for compatibility with LCA. Several authors have demonstrated that process-related emissions depend on composition of input materials and on technological parameters. Thus, we have rigorously selected and combined models so as to generate a relevant life cycle inventory for LCA calculations. The model is able to capture the characteristics of biowaste, more precisely its biochemical composition. As a parameterized model, it is also able to capture complex process dynamics, in particular the microbiological activities and physical processes involved, which will affect emissions and the composition of the final compost. In order to accurately represent specific implementations of different variants of this technology in various contexts, this global model is sufficiently flexible that parameters can be modified. Ultimately, this model will allow for the integration of regional specifities in LCA for the selection of an optimized composting process type. Through this case study, we demonstrate the importance of combining chemical engineering and waste management LCA, and the need to change the way we represent processes.

Sustainable and fair transitions in agriculture: the case for leveraging native maize in Mexico

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Maize biodiversity can be portrayed by the ample variety of colors, from blue, pink, and purple to red, orange, and multi-colored cobs; each variety has distinct characteristics, developed for specialized uses and flavors. This is thanks to the small-scale farmers who keep alive the world´s maize gene bank. They select, save and sow their own seeds, season after season, making each plant uniquely diverse.

Maintenance of this biological diversity is most important in regions where maize is key for food security. This is the case for Mexico. Maize is the most important staple food in the country. However, even when this crop is of paramount importance, native maize varieties are rapidly being lost.

One central cause of maize diversity loss is that heirloom varieties in most cases cannot compete in terms of yield, and market price when measured against hybrids and imported genetically modified grain. Most small-holder farmers cultivating heirloom maize sell it at the same price as the non-native one, in many cases at lower prices than production costs; thus there is no economic incentive for smallholders to keep alive maize seed diversity. And yet they still do it because mexicans are people of maize. But there is a big pressing issue: up to 40% of rainfed maize production which is where native seeds are cultivated is expected to be lost during this century due to its vulnerability to climate change.

The polyculture way of farming maize, the *milpa* system, is a way to reduce vulnerability to climate change while fostering food security. It was developed by Mesoamerican societies being highly efficient in nutrient usage, but as heirloom maize, its practice has been eroding since the green revolution. Qualitative descriptions of benefits surrounding milpas are common among agroecologists. At the same time, there is the technocrat belief that society at large is fed by industrial agriculture ways of production, namely monocultures.

This research uses multiple tools from Industrial Ecology for assessing the sustainability of the milpa production system in the face of the conventional incumbent technology. The focus is a comparative life cycle assessment using the ReCiPe impact assessment method, and ecoinvent and WFLDB databases for modeling the systems using the simapro software. Results show the milpa system for pinto maize has a potential to reduce grain production impact to global warming impact by at least 30%. Discussion on how to improve the maize agriculture at country level draws inputs from the follow-the-thing ethnographic approach, industrial symbiosis, material flow accounting, and backcasting for sustainable development.

This case study is an attept to quantify environmental indicators characterizing the milpa polyculture of native maize varieties. Such are needed as basis for driving discussion among stakeholders concerned with securing the continuous cultivation of heirloom maize at large in the face of volatile climate change and biodiversity loss.

Dynamic analysis of the critical material requirements and recycling opportunities of the U.S. energy transition

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tessa Lee [1]

1. Yale University

The deployment of renewable energy generation technologies has rapidly increased in the last few decades driven primarily by concerns over catastrophic climate change. In the U.S., the Biden administration, in their 2020 election campaign, pledged to decarbonize the U.S. power sector completely by 2035[1], a target replicated in the U.S.'s updated nationally determined contribution[2] submitted as part of the Paris Agreement[3]. This policy ambition demonstrates the potential for high renewable energy penetration in the U.S. in the near-term.
This study uses dynamic material flow analysis to calculate the total quantity of critical material required for several U.S. power sector decarbonization scenarios for wind turbines and solar photovoltaics. The materials modelled are Ag, Cd, Cr, Ga, In, Mo, Pb, Se, Sn, Te, Zn, Dy, Nd, Tb, and Pr. We also investigate several strategies for reducing critical material requirements, including closed loop recycling, reduction in material intensity, and changing market share of subtechnologies (e.g., using crystalline silicon solar panels in place of cadmium-telluride).

Critical metals are the building blocks of today's modern society and are fundamental to many industrial sectors; these metals have been labelled as critical due to concerns over stable supply and the impact of supply constraints on the economy. Understanding the required growth rates of critical metals is important for long term supply planning and for ensuring that the availability of critical metals does not create supply bottlenecks, increasing the price of renewable energy technologies and potentially slowing their roll out. The analysis results show that a transition to a completely decarbonized U.S. energy system by 2050 could require 0.7 – 1.1 Tg of critical materials, representing a six-fold increase in material required compared to business-as-usual. We find that material requirements can be reduce by up to 40% through the strategies modelled, aggressive decarbonization will still require a substantial amount of critical material, with some materials, such as rare earth elements, requiring 60–300 times greater material flows into the U.S. power sector in 2050 than in 2021.
Domestic closed loop recycling is one way to address resource availability challenges, which is especially important for those materials which have virgin supply constraints. Recycling can also contribute to reducing the environmental impacts of producing new technologies by reducing the virgin material extraction required and the associated environmental impacts of extraction. The study finds that the least aggressive decarbonization scenarios have the potential to achieve the highest closed loop recycling rates, at ~20%. The most aggressive decarbonization scenario, on the other hand, can at best only achieve ~6% closed loop recycling. Therefore, recycling will have limited impact in reducing the increases in virgin material demand required by aggressive decarbonization scenarios.

In conclusion, this study finds that, although recycling will be important for reducing virgin material demand, decarbonization of the U.S. power sector will still require significant increases in critical material flow into use. This analysis is useful for informing the development of renewable energy recycling infrastructure and to forecast potential resourcing bottlenecks so they can be mitigated against.

1. The Biden Plan to Build a Modern, Sustainable Infrastructure and an Equitable Clean Energy Future. *Joe Biden for President: Official Campaign Website* https://joebiden.com/clean-energy/.

2. The United States of America. *The United States of America Nationally Determined Contribution.* (2021).
3. United Nations /Framework Convention on Climate Change. Paris Agreement. (2016).

An Assessment of Emissions from the United Kingdom Food System

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Jedidiah Oru-Bo **[1]*****, Eugene Mohareb*** **[1]*****, Libby Schweber*** **[1]**

1. *University of Reading*

Food is a major contributor to global climate change. Globally, food-related emissions are estimated to contribute 31% to total anthropogenic emissions (FAO, 2021). Within the United Kingdom (UK) food-related greenhouse gas (GHG) emissions are estimated to be 35% of total emissions (WRAP, 2021). The UK government has committed to reduce emissions by 68% by 2030 (BEIS, 2020). This work offers a quantification of the annual emissions from the UK food system at the product level and sector levels with the aim of identifying the opportunities for emissions reduction.

This work follows a life cycle approach by quantifying emissions from the agriculture sector through to the waste sector, commonly referred to as cradle to grave. Emissions to farm-gate have been estimated using a literature meta-review following that of Mohareb et. al, (2018). Food commodities have been compiled from a UK annual purchasing dataset. Beyond farm-gate, emissions from the various sectors have been estimated using government published data where available or academic literature. This work provides a comprehensive view of the UK food system estimating emissions based on the average diet of the UK. This work offers a comparison between the UK and US food systems.

The emission cost of food production is estimated at 996.6 kgCO_2e/cap/yr. This puts production as the most substantive share of food system emissions. This aligns with the literature sources that estimate food production contribution as high as 40% of food system emissions (Garnett, 2008; Crippa et. al, 2021). Within the production sector, the consumption of animal products such as meat and dairy product account for over half of these emissions (597.7 kgCO_2e/cap/yr). Beyond the farm-gate, waste management (food landfill), retail and distribution were also substantial contributors, adding 445.04, 170.25 and 145.08 KgCO_2e/cap/yr, respectively. Furthermore, the UK food system has lower emissions across all sectors than the US food system.

Overall, the opportunities for large emissions reductions within the UK can be achieved through further reducing animal product consumption (e.g per capita beef consumption has been in decline for over 50 year). However, it is important to note that animal products often have higher nutrient densities than their plant alternatives (McAuliffe et. al, 2020). Further reductions can be made by reducing the amount of food waste, especially the fraction that is deposited in landfill. The continuous decarbonisation of the energy system will also result in lower emissions across the food system particularly retail and distribution.

Environmental performance of trawling fishing

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ana Cláudia Dias [1], ***Paula Quinteiro*** [1]

1. *University of Aveiro*

The Sustainable Development Goal – 14, launched by the United Nations for the 2030 agenda, "Conserve and sustainably use the oceans, seas and marine resources for sustainable development", specifically addresses the environmental, cultural, and social wealth of these water bodies that provide 16% of the animal protein consumed by the world's population. In Portugal, the most frequently used technique for fishing is trawling, which has been pointed as low selective fishing gear and then harmful to the environment. Therefore, it is important to quantify its environmental impacts from a life cycle perspective using Life Cycle Assessment (LCA). The goal of this study is to apply LCA to evaluate the environmental impacts associated with trawling fishing in Portugal. The fishery process under study is multifunctional, resulting in the production of a number of species, such as Horse mackerel, Atlantic mackerel, Chub mackerel, Blue jack mackerel, Whiting-pout, European squid, European hake, Small-spotted catshark, Curled octopus, and others. The fish landed represented 25% of the total landings in Portugal in 2019.

The functional unit is 1 kg of fish caught. System boundaries include trawling fishing, electricity to produce ice for fish preservation, diesel combustion in the vessel, lubricant oil, and antifouling paint used for fishing ships coating. The inventory data were retrieved from a representative Portuguese company covering 7 trawling vessels in Portugal, with a total production equivalent to 4.06 thousand tonnes of fish during the fishing campaign 2019. Capital goods such as vessels and gear have minor contributions to the overall environmental impacts of fisheries and seafood products, therefore it was excluded from the system boundary. Mass allocation perspective was considered to share the burdens between the target (Horse mackerel, Atlantic mackerel, Chub mackerel, Blue jack mackerel, Whiting-pout) and other secondary species captured. The characterisation factors used in this study are those suggested for conducting a Product Environmental Footprint (PEF).

The results show that the environmental burdens are mainly associated with diesel production and combustion. It is also noteworthy that the secondary species captured contribute more than 10% to the total impacts of the trawling fishery system in analysis.

Therefore, LCA showed its potential to provide supporting information for defining strategies and improving the environmental performance of the trawling fishery, since it highlights that it is important to increase the trawling´s selection by increasing the mesh size or modifying the mesh shape. The increase of the energy efficiency of the fleet and/or use of alternative fuels in the vessels can also contribute to the improvement of the environmental performance of trawling fishery.

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A circular economy potential for Solar photovoltaic in the South East Asian region – Using Life Cycle Assessment and Material Flow Analysis approach

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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With countries racing to achieve net zero, the power sector is one of the key significant contributors to national greenhouse gas emissions and would need to adopt renewable and/or low-carbon alternatives. Photovoltaics is one of the most cost-effective power generation technologies, with grid parity among renewable energy sources. The South East Asian area has 24 GW of installed solar power generation as of 2021; assuming these nations adopt a 100% renewable power supply by 2050, installed solar power capacity might reach 2.4 TW by that year, according to the forecast of IRENA (2022).

Along with the recent increase in solar power installations, the solar module industry has recently grown in the South East Asian region. Up until now, China has held 80% of the market for solar modules, but as a result of foreign investment, several downstream solar module manufacturers have relocated to Malaysia, Thailand, and Vietnam. Furthermore, large-scale solar power facilities have been encouraged through various economic incentive policies in Malaysia, Thailand, Vietnam, and the Philippines. As the number of solar projects increases, more expensive, bigger solar panels and other components will need to be sent throughout the area more quickly.

While direct emissions per unit of electricity generated via renewable systems may have near-zero emissions, however, from the life cycle perspective, the supply chain of photovoltaic may not be near-zero emission. Currently, most solar modules are produced using coal-based power. PV modules have a life span of around 20–30 years. At their end of life, panels must be handled responsibly to reduce the environmental burden. Considering the adoption rate of PV in city/country grid mixes, the large number of PV installations may result in a stockpile of waste upon its end of service.

Furthermore, with the decommissioning of the present PV arrays, new set of PV modules will be required some steel including aluminum. This result in a large demand for raw materials. The principle of urban mining is an alternative method to extract critical minerals and raw materials to produce the new modules. The closing of the materials loop results in a circular economy. For example, recovering aluminum and glass from waste photovoltaic panels has a lot of economic and environmental value. Urban mining has not yet been considered in this region but should be part of the solar module decommissioning process.

This study of methodology is life cycle assessment in evaluating the carbon emissions and materials demand based on both consumer and producer accounting methods to understand the actual impacts as well as reviews the opportunity and technology status in the race to achieve net-zero and urban mining opportunities to support circular economy. Our work could provide insight for the South East Asia as to the way to a sustainable energy transition by supporting the photovoltaic system supply chain, reducing the environmental impact of waste disposal with the adoption of the circular economy.

Dynamic Life Cycle Assessment (dLCA) of a Biorefinery Employing Bakery Waste Oil for Sophorolipids Production with Evolving Technologies

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Sophorolipids (SLs) are promising biosurfactants that have attracted the attention from both academia and industry due to its enhanced properties in comparison to their petroleum-derived surfactant counterparts. Increasingly, researchers are utilizing the waste streams as feedstocks to reduce the economic cost and meet the requirements of sustainability and green chemistry. Although such waste valorization minimizes the use of first-generation substrates, the systematic environmental impacts must be assessed by considering the different materials and processes to improve the sustainability of the process. For this reason, the dynamic Life Cycle Assessment (dLCA), due to its iterative nature, is applied to identify the tradeoffs between potential environmental impacts early in the research and development phase. Our previous dLCA traversal has demonstrated that food waste hydrolysate (FWH) is a promising hydrophilic carbon source, while oleic acid as the 1st-generation hydrophobic carbon source, should be a significant pollution source. Hence, this work evaluates the environmental performance of using bakery waste oil (BWO) as a hydrophobic feedstock. The 4th and 5th traversal of the *dLCA* showed that although BWO brought more environmental pollution than the pure first-generation substrate, proper pH regulation could effectively reduce its environmental burden. In the 6th traversal, the further comparison showed that if SLs production is applied batch fermentation, using BWO as substrate was more environmentally friendly than using FWH. This paper suggests that multi-technique incorporation, such as feeding with FWH and BWO together equipped with fed-batch fermentation and *in-situ* separation, may further reduce environmental impacts, meanwhile providing a clear direction for the experimentalists.

The spatiotemporal evolution of carbon emissions and resource inequality in China's interprovincial coal trade

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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As coal is the most plentiful resource on earth, its recent consumption rebound demonstrates the conflict between energy demand and climate change. China is the world's largest coal user, whose energy structure heavily depends on coal resources, with 4.05 billion tonnes of raw coal (62.2% of total energy consumption) in 2020. Coal resources are abundant in northern China, with around 73% of exploration coal reserves. However, the demand side is concrete in southern China. With the increasing domestic energy demand, the large scale of coal transfer from north to south China exceeded 2.2 billion tonnes in 2020. Hence, the critical question of coal consumption is the mismatch between coal production and consumption in China, aggravating resource inequality and environmental emissions. An accurate assessment of transfer flows in interprovincial coal trade is essential to reveal the resource inequality of inter-regional trade.

Embodied energy trade and embodied carbon emissions have been widely assessed using the environmentally extended multiregional input-output (MRIO) method; nevertheless, the strong assumptions between currency exchange and the physical satellite matrix can result in a large deviation from reality. The physical trade flows of energy were usually neglected because of the trade complexity and data available. In this study, we focus on the transaction of physical coal flows in interprovincial energy trade to decrease this deviation. First, we established a multi-source-based coal database fused by interprovincial coal commerce, coal transportation mode, transportation expenses, transport network, coal prices, customs, and statistics data of 30 provinces from 2015 to 2020. Second, the trade pattern of interprovincial physical coal flows among 30 provinces was characterized by constructing the linear programming model of minimal system costs with 4 decision variables: interprovincial total coal outputs, coal inputs, and the total transport quantity of different coal transport modes.

The results showed the net interprovincial coal trade was 1824.6 million tonnes (Mt) in 2015 and rose to 2080.4 Mt in 2020. The interprovincial trade volume of Inner Mongolia, Xinjiang, and Yunnan increased, and core links are Shanxi-Hebei, Shanxi-Shandong, Shaanxi-Henan, Xinjiang-Gansu, and Inner Mongolia-Hebei. In addition, the regional coal trade is discussed based on the Chinese geographical division. The internal-region cycle of coal trade is lower than the external-region cycle, where only the internal-region cycle rate of southwest, east, and central China increased. By the life cycle assessment with cradle-to-gate system boundaries, interprovincial physical coal trade led to 7659.7 Mt cumulative CO2eq from 2015 to 2020. From a production-based perspective, Inner Mongolia, Shaanxi, and Xinjiang were 35.7, 31.7, and 25.6 times higher than the consumption-based cumulative emissions. However, the total resource inequality of interprovincial physical coal trade was 1.57 in 2015 and slowly decreased to 1.37 in 2020, with an average within-area inequality accounting for only around 6%. North and east China are low-emission, high-inequality regions, whereas northwest and southwest China are high-emission, low-inequality regions. The scenario analysis presents that stated policies scenario of renewable energy power generation can not significantly decrease the interprovincial energy crisis and life cycle carbon emissions of energy use till 2030. Policymakers should consider the inequalities and develop a fair energy distribution and non-radical coal transition measures to ensure a sustainable and climate-neutral energy future.

Quantifying material flows to integrate tomato greenhouse horticulture into a circular industrial ecosystem

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Alexander van Tuyll [1], ***Alexander Boedijn*** [1], ***Martine Brunsting*** [1], ***Tommaso Barbagli*** [1], ***Chris Blok*** [1], ***Cecilia Stanghellini*** [1], ***Martin van Ittersum*** [2], ***Andries Koops*** [3], ***Erik de Lange*** [3], ***Jolanda van Medevoort*** [4]

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Greenhouse horticulture faces several sustainability challenges. Amongst these, reducing environmental impact is essential, but not enough. The current linear supply chains within the horticultural sector not only result in environmental impact; they also deplete a variety of finite natural reserves. This is why moving towards more 'closed loop' supply chains, embedded within a circular economy, is becoming increasingly desired.

One of the obstacles in implementing a circular economy are knowledge gaps about the quantity and quality of input- and output flows of production processes. The aim of our 2022 paper, published in the Journal of Cleaner Production, was to bridge such knowledge gaps. This was done by detailing the resource input and -output of a typical high-tech glasshouse tomato crop in the Netherlands. In particular, this paper focuses on six material flows potentially suitable for relatively short-term re-use and/or substitution in a circular economy: biomass, water, nutrients, carbon dioxide, plastics and substrate.

We describe how data were collected about the sub-processes involving each of the material flows, the accuracy and range of such numbers, and how their consistency can be finally verified. The results are visualised (e.g. material flow diagrams) and the potential of and obstacles for recycling each of the six material flows is discussed. For instance, the results show that there is a good potential for recovering mineral components for fertiliser production from residual biomass (i.e. stems and leaves), where over half of Mg, Ca and S end up, at 58%, 70% and 70% respectively. However, a barrier is the plastic waste that is mixed together with the residual biomass, requiring changes either in the production system (e.g. biodegradable materials) or improved separation techniques at waste processing companies. By quantifying the flows per unit of produce (1 kg tomato), we provide numbers for dimensioning possible symbiotic production processes, such as 'cross-overs' with aquaculture, animal husbandry and mushroom production. Examples of such cross-overs, where material flows between greenhouse horticulture and other production systems are exchanged, have also been quantified and explored conceptually in separate white papers.

Our future research aims to build on the previous paper by focusing on one material flow: nutrients. This flow was chosen due to challenges related to quality, availability to plants, and food safety, as well as unique properties of greenhouse horticulture like closed-loop irrigation systems and a high nutrient throughput per hectare as a result of high productivity. In particular, we focus on phosphorus due to its environmental impact (e.g. eutrophication) and projected scarcity. Circular sources of phosphorus will be necessary whilst minimising diffuse emissions to the environment, after which recovery is difficult. Multiple circular sources of phosphorus show potential, including cross-overs with other sectors within the industrial ecosystem (e.g. those covered in previous white papers, but also waste water treatment plants). With this research, we aim to work towards solutions to include greenhouse horticulture in a closed nutrient loop and better understand the niche it can occupy in this circular industrial ecosystem.

Unpacking domains and trends in food environments - a bibliometric analysis

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Isaac Guzman Estrada [1]***, Eugene Mohareb*** [1]***, Stephen Gage*** [1]

1. *University of Reading*

Food systems and, in particular, urban food systems have been gaining attention in the last 20+ years; based on a review from Zhong, et al (2021), from 2000s onwards there has been a 'stable-growth' period on urban food systems research. Food systems are multidisciplinary and interconnected with other systems and sub-systems, with many entry points to study them, currently existing a wealth of literature. Key topics have included food security (Vilar-Compte, et al., 2021), value chains (Djekic, et al., 2018), diets (Montez De Sousa, et al. 2022), consumption in cities (Guibrunet and Sánchez Jiménez, 2022), urban food growing (Warren,et al 2015), etc. However, a rigorous examination focusing on food environments is an important gap in food systems analysis. Food environments are the interface of the food systems (food production and agri-food value chains) and diets (consumption) (FAO, 2016). The HLPE (2017) defines them as the "*physical, economic, political and socio-cultural context in which consumers engage with the food system to make their decisions about acquiring, preparing and consuming food*". The aim of this research is threefold. 1) identify areas and categories of research, 2) identify authors and papers that contributed with knowledge foundation, 3) identify research trends and future research opportunities. Furthermore, it is of interest of this research to identify clusters of knowledge and conceptualization of food environments. Identify on which territorial scope they are usually use. Finally, on which indicators and measurement they relay.

A bibliometric analysis was used to review the published material on food environments. Bibliometric analysis is a quantitative method to determine the status of specific research which allows to look into knowledge of cluster, understand relations between papers and authors, and shed light in future research direction (Pritchard, 1969). By using co-word analysis (Callon, et al 1991), bibliometric coupling (Kessler, et al. 1963), and network visualization (Chen, et al., 2010) to investigate the topic's relations within the food environment concept is analyzed among cited publications to understand the timescale development of themes.

The literature search was based using a query to investigate "food environments" and "foodscapes", two concepts usually used interchangeably, using the time period of 1992-2022. Publications from 2007 onwards had a constant growth reaching 267 in 2022 alone, prior to that under 10 publications per year. The top three subject areas, covering 63% of research are Medicine, Social science and Nursing, pointing to a predominance on health-related research. In terms of region, there is a broad scope of territories studied; nevertheless, high-income countries dominate, representing 42% of all the publications, followed by low and upper medium income. Moreover, Anglosphere countries, with 57% publications, dominate the research field. The complex relationships within the food system, the way it is govern and the environmental and human impacts, call to advance efforts of conceptualization and characterization for a deeper understanding of the role of the food environments in the health and sustainable domains of diets (Carducci, et al., 2022; Pettenati, et al., 2019; Wolfenden, et al., 2021; Downs, et al., 2022).

Current and prospective environmental consequences of integrated vs added photovoltaic roof applications

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Mara Hauck [1]***, Mitchell van der Hulst*** [2]***, Lia de Simon*** [1]***, Diana Godoi Bizarro*** [1]***, Ando Kuypers*** [3]***, Mirjam Theelen*** [3]***, Sjoerd Herlaar*** [1]

1. *TNO, Climate, Air and Sustainabilty,* ***2.*** *Radboud University Nijmegen, Department of Environmental Science,* ***3.*** *TNO partner in Solliance*

Climate targets and economic competitiveness have led to large scale employment of photovoltaic (PV) devices. Next to that, technological developments in second and third generation PV, thin-film and flexible cells, has widened the possible application surfaces of PV. An example is building integrated PV, where the PV panels are an integral part of the building envelope. These building integrated photovoltaics (BIPV) are PV materials used to replace conventional building materials in parts of the building such as the roof, façade or windows. BIPV are distinguished from building added photovoltaic (BAPV) where the panels and frames are added to the building with their mounting structure (e.g. on a roof already covered by tiles) or stand-alone land based PV such as solar farms. The differences in these applications might lead to differences in available technology choices, techno-economical and environmental performance. To prevent negative consequences during transition to a zero-carbon energy supply, it is important to gain knowledge on these differences as early as possible.
An accepted tool to get insight in the environmental performance of a product is life cycle assessment (LCA). Although several authors contributed to shedding light on the differences in environmental performance between building added and building integrated PV, definition of integrated PV is not always restricted to the ones replacing part of building materials. Moreover, few authors (e.g. Kristjansdottir et al., 2016) have systematically compared the environmental impacts of providing electricity to houses using different PV systems. However, none of them has investigated these scenarios considering the electricity transition or looking into the inherent differences in replacement options. The aim of this research is to compare the environmental profiles for providing electricity to an average Dutch family house using building integrated or added systems. All systems were designed to fully provide this electricity demand in the first year. Over the 50 years period of analysis part of the electricity is supplied by the grid due to degradation. Differences in replaceability are also taken into account. Scenarios are compared under current and expected electricity provision from the grid.
The following technologies are considered in this research:

- flexible Copper-Indium-Gallium-Selenide (CIGS) semifabricates integrated in steel rooftiles "*Integrated CIGS*"
- rigid CIGS modules added on ceramic roof tiles "*Rigid CIGS*"
- rigid crystalline silicon modules, added in ceramic roof tiles "*Rigid x-Si*". These are included as a benchmark as this is currently the most commonly PV technology.

Additionally, a scenario has been defined where added PV modules can be replaced after 30 years with more efficient cells. The current and expected future Dutch electricity mix from the grid are used in those scenarios. Inventory data for CIGS modules is taken from in-house data of the mass customization line at TNO and adapted from Van der Hulst et al. (2020). Silicon modules are modelled based on literature. All scenarios are assessed using ReCiPe, 2016. Preliminary results show that, thin-film cells have environmental benefits over benchmarks and flexible over rigid (in terms of carbon footprint and most impact categories). With the current electricity mix, replacing modules with higher efficiency modules has carbon footprint benefits (but not necessarily for other impact categories). If the grid mix itself contains more renewables, this benefit vanishes. In the presentation we also show the effects of changing electricity generation in the production and waste treatment.

Spatially explicit LCA of silicon production: the importance of system levels in environmental assessments.

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Silicon is a relevant material for a low-carbon society with applications that range from aluminium alloys for light vehicles, the electronics and chemical industry, energy storage markets, or as a precursor of photovoltaic systems and silicones with a variety of functions. However, this highly valuable metalloid is energy and carbon-intensive in production, with impacts dependent on regional parameters such as the raw material sourcing and composition, process input, and the energy supply at production. China produces around 75% of the global Si supply, followed by Russia and Brazil, however, the published LCAs for silicon consider European production conditions. There is a need to increase our understanding of the environmental impacts of producing this central material, considering the impacts of process characteristics (yields, energy efficiency) and value chain settings (the source for carbon, energy, and process inputs). It is a priority of the European Union to increase internal production, where Si production presents an interesting and highly relevant case for spatially-specific LCA. The spatially-specific assessment applies to three system-specific levels: process factors, value chain factors, and impact vulnerability. We conduct parametric and spatial Life Cycle Assessment to evaluate the different contributions to the environmental impact of silicon production across different countries. The results distinguish between impacts mostly influenced by the process, the market, and geographical vulnerability conditions, and allow us to differentiate these aspects when incorporating them into strategic planning. This research constitutes a working example of how spatially explicit LCA can be used in technology decision-making.

Sustainability trade-offs among blue foods in North Sumatra

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Patrik Henriksson [1]***, Emmy Iwarsson*** [2]***, Alon Shepon*** [3]***, Edi Iswanto Wiloso*** [4]***, Adisa Ramadhan Wiloso*** [5]

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Blue foods (foods from aquatic environments) are an important source of animal protein and many essential micronutrients in Indonesia, but the environmental and socioeconomic consequences related to their production varies greatly across species and production systems (Gephart et al. 2021). As the supply of blue foods from capture fisheries is biologically limited, aquaculture has grown rapidly to keep up with demand. However, most of the aquatic species promoted by the Indonesian government and transnational corporations are high-valued species, such as shrimp and groupers. These are more resource demanding to produce, remain unaffordable for those most in need, and are not optimal in terms of nutritional density (Henriksson et al. 2017; Shepon et al. 2021). The present study subsequently uses North Sumatra as a case study to explore potentials for a better Blue Food strategy, with regards to resource optimisation, environmental emission reductions, and food security. We chose North Sumatra for our case study as it is an ecologically rich area that is being rapidly exploited by several competing industries, including palm oil and mining, but with a persistently high rate of stunting. Our approach is derived from current consumption patterns of Blue Foods, mapped using spatial material flow analysis, the SUSENAS household survey dataset, nutritional data, and LCA results. We, in turn, use these data to explore possible correlations between regencies, blue food production, environmental impacts, nutritional quality, and stunting rates. Our preliminary results indicate that four times more fish is consumed than chicken in North Sumatra, the most popular terrestrial meat product. Of these fish, most (85%) are procured fresh, while 15% are purchased preserved (most commonly dried). Roughly half of the fish consumed fresh originates from aquaculture, while almost all preserved fish consumed are finfish from capture fisheries. The local cost of preserved finfish is roughly twice that of preserved finfish, while the most expensive species are shrimp, lobsters, squid, and cuttlefish, species also commonly destined for export. The material flow analysis, in the meantime, indicate that only about 187 billion IDR worth of blue foods are exported internationally from Sumatra, while domestic exports amount to 1.8 trillion IDR. These domestic exports, however, are mainly from the province of Lampong, the southernmost province of Sumatra, while most of the 1.9 trillion IDR worth of domestic imports are to North Sumatra. This suggests that the province of North Sumatra is Blue Food deficient. Meanwhile, the Indonesian government is planning to establish more than 130 ‘aquaculture villages’ to double shrimp production by 2025. Environmental impacts related to shrimp farming, including land-use change and increased demand for fishmeal, are therefore worrisome, as it may exacerbate inequalities by depriving lower socioeconomic households from an essential source of nutrients. In response, we propose a Blue Food portfolio that promotes species that result in less environmental impacts, are cheaper to produce, and maximises nutritional output.

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Assessing the Global Sustainability Impacts of Energy Procurement Switching Strategies: the case of Italy during the Russia-Ucraine war

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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The war between Russia and Ukraine has led to a global geopolitical crisis (Bricout et al., 2022).

In particular, in a very short period, European countries have evidently shown the criticality related to the dependence on energy supply from Russia and the lack of energy autonomy (Austvik, 2016; Ruble, 2017; van der Zwaan et al., 2021).

One of the most important aspects of the crisis is related to the energy market turbulence: their joint effects have resulted in relevant variations in the prices of energy sources.

In response to these events, the European countries have been adopting some measures, mainly related to the following types of interventions: (1) Replacement of energy source suppliers (e.g., switching the natural gas supply from Russia to Algeria); (2) Reduction / Saving consumption; and (3) Replacement of energy source typology (e.g., switching from methane to coal or renewable sources) (Clifford, 2022; European Commission, 2022).

These measures have been aimed at obtaining a progressive detachment from the Russian energy supply dependency, while not penalizing the national economies, i.e., trying to leave unchanged the overall quantity of energy supply.

This paper focuses on the Italian strategy of replacing energy source suppliers – referring to the previous point (1) – and is aimed at investigating the potential consequences of such a strategy in terms of the three sustainability dimensions at both the national and global scale.

In particular, building on the Global Emission Chains developed by Fraccascia and Giannoccaro (Fraccascia & Giannoccaro, 2019), we develop a tool based on Environmentally-Extended Input-Output tables, useful to compute an – as much as possible – optimal and non-redundant choice of 14 indicators, which take into account all the three sustainability areas, at the level of the single industry of the single country.

Relying on the data from EXIOBASE 3.4, such a tool has been adopted to study the previously mentioned Italian case. As a result, numerical changes in the sustainability indicators driven by the adoption of the new Italian energy supply strategy can be highlighted, at both the global level and at the level of single countries.

Sustainability impacts of the strategy are finally discussed.

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Disassemblability, recyclability and ecodesign assessment to promote the circular economy in the automotive sector

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Abel Ortego [1], ***Michelle Sesana*** [2], ***Veronica Antonello*** [2], ***Antoinette van Schaik*** [3], ***Mattia Calabresi*** [2], ***Marta Iglesias*** [4], ***Alicia Valero*** [1], ***Ricardo Magdalena*** [1], ***Samuel Alcoceba*** [1]

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Advances towards cleaner vehicles are encouraging the continuous renovation of vehicle fleet so it is expected that in the following decades a complete renovation will take place. This new generation of vehicles will significantly reduce its fossil dependency. But in contrast, it will demand a huge quantity of other kinds of natural resources being some of them even scarcer than oil.

Some of these resources will be necessary to manufacture the following components: batteries (Co, Ni, Mn or Li); LEDs for lighting (Ga, Ge, Y); permanent magnets for motors (Nd, Dy, Pr); electronic units (Au, Ag, Sn, Ta, Yb), different kinds of sensors (Ce, Tb, Se, La), infotainment screens (In); automotive high performance steel or aluminum alloys (Nb, Mo, Cr, Ti, V, Sc, W).

Unfortunately these resources are finite and some of them are very scarce being even considered as critical for the European Commission and other institutions from several perspectives such as vulnerability, economic importance, supply, or ecological risks.

This research presents a tool to support the transition of the automotive sector towards Circular Economy (CE), by providing a concrete demonstration of how the industry can benefit from the adoption of Circular Economy practices and principles, both from a business and a technological perspective.

One of the main encountered issues highlighted by the automotive actors, refers to the huge information gap existing between Beginning-of-Life (BoL) and End-of-Life (EoL) actors along the whole automotive value chain up to the final consumers.

To this aim, a web-based platform is presented as a new information-sharing tool among all stakeholders, both in forward and backward directions, ensuring secure access and confidentiality. The platform makes information available through specific modules that are designed according to each stakeholder's needs. The Circularity web application provides helpful information and 26 KPIs in a secure way to each stakeholder to improve circularity along the vehicle's value chain.

Accordingly, manufacturers share information with dismantlers and recyclers regarding the material composition of already-designed car parts. Dismantlers generate information regarding times, required tools, costs and procedures needed to dismantle that specific car part. Dismantlers also share information with manufacturers about recommendations to improve design for disassemblability and with recyclers about dismantling levels that can be achieved and related costs. In turn, recyclers share with manufacturers the material recovery potential of that specific car part and recommendations to improve design for recycling. The Recycling module will provide recycling rates/materials recovery rates with dismantlers depending on the disassemblability level achieved. In addition, the system generates with all such information a set of key indicators differentiated by the type of user.

Moreover, the tool includes a virtual reality module where the dismantling operator can visualize the procedures to dismantle a car part as well as some related metrics (such as duration of the procedure, number of steps or comments provided).

As main results disassemblability, recyclability and eco-design modules are presented with data about car electronic components and feedback from dismantlers and recyclers to eco-designers.

Uncovering the spatiotemporal evolution of the global wind energy system: A high spatial resolution material stock and flow analysis

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Shangjun Ke [1], *Gang Liu* [1], *Srinivasa Raghavendra Bhuvan Gummidi* [1]

1. University of Southern Denmark

Wind resource-rich countries have made ambitious plans for wind energy development to achieve their national determined contribution by 2050. In the last two decades, the global cumulative wind capacity has increased from 7.5 GW in 1997 to 564 GW in 2018. The upcoming wave of decommissioned wind turbine material will have a wide range of environmental impacts on air, rivers, and soil in various countries. For instance, the recycling of wind turbine blades is particularly challenging as a consequence of its enormous waste generation, environmental hazards, dispersed geographical distribution, and inflated cost of transportation. Understanding the spatiotemporal evolution and material flows of global wind turbine material is crucial for future wind farm employment, environmental conservation, and end-of-life management strategy. However, previous studies on such issues were primarily conducted on a national or regional scale, due to a lack of more spatially refined data, and thus could not reveal the spatial patterns and dynamics on a global level. This study integrated material flow analysis (MFA) and geographic information system (GIS) data to uncover the spatiotemporal evolution of the global wind energy system and its stocks and flows at a previously unprecedented high spatial resolution. The quantification approach is based on a global wind turbine spatial database and regression models, combined with a capacity class-based estimation for missing datasets. The results could support researchers, practitioners, and policymakers in understanding the geographical availability of blade waste material, identifying local hotspots and opportunities, and assessing potential circular economy pathways. (This abstract is for the Symposium on Industrial Ecology for Young Professionals).

Nitrogen and Phosphorus Footprints of the Agriculture Sector in Indonesia

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Introduction

Nitrogen (N) and phosphorus (P) are primary nutrients for agricultural production. N, in its reactive form (Nr, nitrogen species except for N_2 gas), and P necessarily control the growth of organisms. However, loss of N and P can be detrimental to the environment and human health. A footprint measures the impact of human activities on the environment. N and P footprints quantify how much N and P are released to the environment from anthropogenic sources.

Indonesia is one of the world's largest producers and exporters of agricultural commodities[1]. The agriculture sector potentially causes high emissions of N and P in Indonesia due to the production of food products such as palm oil, cocoa, coffee, rice, etc. Previously, a study by Wirasenjaya et al. (2023)[2] assessed Indonesian N and P footprints for the food sector using a bottom-up approach. Using a different approach, this study calculated the N and P footprints of the agriculture system through all economic sectors in Indonesia to provide a quantitative basis for essential policy recommendations in achieving sustainable N and P management.

Material and Methodology

The nutrient-extended input-output (NutrIO) approach developed by Oita et al. (2021)[3] was used to analyze N and P footprints in Indonesia. Based on the material flow analysis, the physical N and P inputs to Indonesia were connected with the national economic activities from four sources (chemical fertilizer, manure fertilizer, agriculture residue, and feed). The Indonesian input-output table for 2010 was used as a base table for the calculation.

Results and Discussion

The N and P footprints of the agriculture sector in Indonesia were estimated as 6,712.7 Gg-N and 779 Gg-P in 2010. Chemical fertilizer as agricultural production input contributed the highest to these footprints. This is due to excessive chemical fertilizer use by the farmers in food production from their belief that higher application of chemical fertilizers will lead to higher yield. The rice milling products sector was observed to have the highest N and P footprints. A high dependency on chemical fertilizers to meet the high indirect input for the rice milling products sector stimulates this sector's high N and P footprints. The demand for animal-based products is also high in Indonesia. The demand for poultry products at the consumption level is notably higher than the other animal-based products. Consequently, poultry products largely influence the N and P footprints in Indonesia. In addition, Indonesian high N and P footprints are due to people's dietary choices.

Conclusion

The findings of this study are expected to support the policymakers in their efforts to formulate policy options to reduce N and P loss from the agriculture sector. Furthermore, the Indonesian government, researchers, educators, and citizens would be able to focus on sustainable N and P management strategies. However, this study only considered the non-energy sector as N and P input. Therefore, the energy and industry sectors can be included in future works to provide a more comprehensive view.

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Life Cycle Assessment of Gum Waste Batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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The world's battery demand and production are growing drastically. Currently, the market is dominated by lithium-ion batteries, which contain many critical raw materials: cathode active materials often contain nickel and cobalt, and most anodes are made of natural graphite. Additionally, battery production is an energy-intensive process. Therefore, battery production has a large carbon footprint, causes mineral resource depletion, and risks adversely impacting human health and the ecosystem. Hence, a detailed analysis of battery production's environmental impacts to identify hotspots is vital for any new battery technology or production process. A new idea for eco-friendly, low-cost bio-based materials is substituting active materials or binders with material produced from gum waste.

Gum waste is a natural waste that cannot be treated or disposed of easily due to its highly acidic contents and sticky features. Different types of gum wastes can undergo pyrolysis to obtain micron-sized functional carbon, all of which display high tap density (1.4–1.7 g cm^{-3}) and excellent electrochemical performance at high current density for a long time and many cycles. These properties make gum waste a promising alternative battery material.

Life cycle assessment (LCA) is a standard approach for quantifying the environmental impact of a product or process throughout the whole life cycle, from the extraction of materials to end-of-life. The gum waste batteries are in early-stage development, making primary data collection and how to proceed with life cycle inventory (LCI) are challenging. Here, we are carrying out a prospective LCA to estimate the environmental impact of a Lithium–Sulphur battery using gum as an alternative binder. This gum waste battery is produced on a laboratory scale.

The LCA is implemented with a functional unit of 1 kWh of energy storage capacity, and the system boundaries are cradle-to-gate. The goal of doing LCA is to show the environmental benefits of gum waste batteries and find the hotspot of environmental impact and a possible optimization in process or materials. Regarding the LCI, foreground processes are modeled using laboratory measurements and records. Background processes are filled using the ecoinvent database. ReCiPe 2016 is used as a Life Cycle Impact Assessment method.

The result demonstrates the environmental impact of each component and the entire gum waste battery cell. The substitution of natural graphite with gum waste has multiple environmental effects. It would not only decrease resource depletion of a critical raw material but also would reduce the total carbon footprint of battery production.

These findings would benefit different types of batteries and their effects on the environment and foster the comparison with other life cycle assessments on the production phase of different battery types. Scaling up the use of biogenic wastes as battery raw materials would strengthen the Circular Economy from a bioeconomy perspective and support the decarbonization of the energy sector.

Keywords: Batteries, gum waste, life cycle assessment, anode, environmental impact

Normalization factor database for life cycle impact assessment in China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

beijia huang [1], ***Zhihao Chen*** [1]

1. University of Shanghai for Science and Technology

Normalization is applied to calculate the magnitude of an impact relative to the total impact of a given reference in Life Cycle Assessment (LCA). Normalized profiles of environmental impacts are dependent on geographical areas due to differences in the industrial and economic activities. Till now, China has not developed normalization factors to conduct life cycle assessment analysis. The purpose of this research is to propose normalization factors (NFs) database covering key environmental impact categories in a Chinese context to fill the research gap. To establish the local database, we collected the domestic inventory of emission and resources extraction in China and calculated the normalization factors based on the international model ReCipe2016. Five environmental impact categories in this research needs data conversion, data substitution and data supplement by extrapolation. The main contribution of this paper is establishing a normalization factors database of life cycle assessment in China. The normalization factors of 18 impact categories includes normalization factors at the national and individual levels and the substance contribution proportion of the 18 environmental impact categories are calculate. We discussed the data uncertainty and concluded five uncertainty of data sources in this study. Two major sources of uncertainty are identified based on data quality and robustness of the extrapolation strategy: data gaps and uncertainty on CFs for each impact category. The presented database provides the LCA researchers a starting point for a subsequent weighing step and improve the accuracy of LCA study at the Chinese territory. The data substitution and supplement fills the data gap but also brings the data uncertainty. We assess the uncertainty of the result by the data quality matrix and proposed the measures to promote comprehensiveness of inventory after defining the sources of the data uncertainty. So, future emission monitoring and statistics to reduce the uncertainty and increase the data availability is strongly encouraged.

Environmental Impacts Assessment of Future Hydrogen Production

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Shijie Wei [1], ***Sangwon Suh*** [2], ***Romain Sacchi*** [3], ***Vassilis Daioglou*** [4], ***Simon Bennett*** [5], ***Bernhard Steubing*** [6]

1. Leiden University, CML, 2. University of California, Santa Barbara, 3. Paul Scherrer Institute, 4. PBL Netherlands Environmental Assessment Agency,, 5. International Energy Agency, 6. CML Leiden

Climate change and net-zero commitments are accelerating the shift from fossil fuels to alternatives like clean hydrogen. However, for a complete picture of the suitability of emerging hydrogen production pathways in terms of greenhouse gas (GHG) emissions and other environmental impacts, it is essential to involve upstream processes to quantify their environmental benefits from a prospective life-cycle perspective. Thus, in this paper, life cycle inventories (LCI) of 24 types of hydrogen (coal gasification w/o and w/ CCS, natural gas steam reforming w/o and w/ CCS, biomass gasification w/o and w/ CCS, water electrolysis of alkaline electrolyzer (AE), protein exchange membrane (PEM), solid oxide electrolysis cell (SOEC) sourced from electricity of grid, wind-onshore, wind-offshore, solar PV, nuclear and hydro power) in global 26 regions and at a worldwide level were developed. By integrating the production efficiency improvement, materials demand decrease, and electricity mix decarbonization, the environmental impacts of these hydrogen production pathways from 2020 to 2050 in two Shared Socioeconomic Pathways (SSP), SSP2-Base (the "middle-of-the-road" pathway without climate policy) and SSP1-RCP19 (the "inclusive and sustainable development" pathway with efforts to reach net zero by 2050) scenarios, were assessed by prospective life cycle assessment (pLCA). Finally, the LCI database for future global hydrogen production pathways was created. Dynamic LCA results based on this database were used to identify the major processes that contribute significantly to GHG emissions and other environmental impacts, as well as key driving factors that contribute to mitigating these environmental impacts. With these results, policy makers could be informed by a prospective viewpoint so as to make a medium- and long-term decision.

Life cycle greenhouse gas emissions and mitigation opportunities of High Speed Railway in China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Zimeng Cai [1], ***Ming Xu*** [1]

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High-speed railway is considered as a clean mode of transportation that can reduce greenhouse gas (GHG) emissions in the transportation sector. However, the high-speed railway system involves complex composition, large infrastructure projects, and high energy consumption, leading to GHG emissions from multiple processes throughout its life cycle. This study aims to conduct a comprehensive life cycle assessment (LCA) of a conventional high-speed railway in China to analyze its GHG emissions.

The study will establish a GHG emission inventory by collecting data and conducting LCA, and will suggest ways to reduce emissions. The life cycle of high-speed railway will be divided into three stages: construction, operation and maintenance, and scrapping and dismantling. This study will calculate the total GHG emissions and identify the stage and process with the highest contribution. Options for disposal will be evaluated to determine the optimal approach with the lowest GHG emissions.

The results of this study will provide insight into the total GHG emissions of the high-speed railway life cycle and the contribution of each stage, offering useful suggestions for reducing GHG emissions in the high-speed railway industry.

The consequences of consumer behaviors and environmental consciousness among various races on household carbon footprints in the United States

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Jiahuan Wang [1], *Yosuke Shigetomi* [1], *Andrew Chapman* [2]

1. Nagasaki University, 2. Kyushu University

Our daily activities (i.e., household consumption) are the dominant driver of the national carbon footprint. The carbon footprint of household consumption, household carbon footprint, varies among individuals depending on a person's location, habits, and choices. In addition, recent studies of household carbon footprints also take the emission inequality among households into account. To achieve an equitable reduction in greenhouse gases (GHG), understanding the influential factors on the household carbon footprint in detail is critical.

Against this backdrop, we focus on race as a key factor in a reduction in household carbon footprints in immigration-rich nations such as the United States (US). Previous studies (e.g., Chapman et al., ***Environ. Res. Soci. Sci***., 2021) highlight the importance of considering environmental protection and climate change policies cognizant of race being affected by cultural background through the survey taken in the US.

This study, therefore, aims to identify the characteristics of household carbon footprints by race by exploring the potential role of cultural background. The results and discussion are expected to lead to policy implications for climate change mitigation in an equitable way, cognizant of factors related to various races (e.g., environmental consciousness).

The methodology used is an environment input-output analysis (EIOA) with a multi-regional input-output (MRIO) table. We quantified the historical US carbon footprints of households by racial group via a combination of EXIOBASE v3 and the household budget survey in the US between 2000 and 2011 which is covered by EXIOBASE.

Here we detail the preliminary result of the US carbon footprints of households by race of the household head in 2011. Households in "White and all other races" generated the largest per-capita carbon footprint at 39.3 t-CO_2eq/capita, followed by those in "Asian" at 27.0 t-CO_2eq/capita. "Black or African American" households accounted for the lowest footprints at 23.9 t-CO_2eq/capita. At the sectoral level, "transport, post, and telecommunications" contributed the most, by more than 40% to the total carbon footprint across all racial groups. The two races ("White and all other races" and "Black or African American") with the greatest gap in carbon footprint are observed in the sector of "waste and other services". "Asians" accounted for the lowest footprint of "utilities" (e.g. electricity and gases in a home) compared to the other groups. These trends may also be related to differences in the average income level, education attainment, and environmental consciousness which may also be affected by cultural backgrounds between races.

We will demonstrate the further results and discussion of the policy implications for GHG emission reduction cognizant of different races and future immigrants in the US at the conference.

Lifecycle Energy and Carbon Emissions of Water Supply in a Water-Stressed City: Comparing Long-range Piped and Decentralized Water Supply in Paju, Korea

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Yiseul Hong [1], ***Jooyoung Park*** [2]

1. Korea university, 2. Seoul National University

Despite a net-zero movement in Korea's water sector, comprehensive assessments of lifecycle energy and carbon emissions associated with urban water systems in the region are lacking. Focusing on a water-stressed city, Paju in Korea, this study aims to evaluate lifecycle energy and carbon emissions across the entire urban water cycle from abstraction to discharge and reclamation. Without reliable local water sources, Paju has already increased water imports and diversified water sources, but its water stress is expected to increase further due to an increase in water demand, saturated and aging water infrastructure, and climate change. This poses a question how Paju needs to manage its water while aligning with water sector's net-zero target. To compare water supply options in terms of lifecycle energy use and carbon emissions, we compared conventional long-range piped water supply options (local supply and inter-basin water transfer) and decentralized circular water options (rainwater harvesting, greywater reuse, and wastewater recycling). For lifecycle energy, we considered electricity consumption, embodied energy in pipelines and chemicals used, and energy avoided from potential water savings and reduced volume of wastewater treatment. Our preliminary analysis on the lifecycle energy showed that conventional piped water supply options were still more energy-efficient than circular water options. While the energy intensity of conventional piped water supply was the lowest, the circular water supply options adopted in this city were less energy efficient because of the advanced treatment required for industrial use. In addition to lifecycle energy, we will also analyze direct greenhouse gas emissions from wastewater collection and treatment as well as indirect emissions from electricity consumption and embodied energy in pipelines and chemicals. Understanding water-related energy and carbon would inform energy-efficient and low-carbon water management and planning for water-scarce cities.

Decarbonisation of Food Loss and Waste: A Case Study of Chicken Feet Supply Chain in the UK

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Yiming Sui [1]***, Eugene Mohareb*** [1]***, Stefan Smith*** [1]

1. *University of Reading*

Food loss and waste (FLW) has become a significant issue in recent years. Studies showed that 13.8 % of total food, equivalently more than 1.3 billion tons of food were wasted (Gustafsson et al., 2013), which was responsible for one third of global anthropogenic food greenhouse gas (GHG) emissions (FAO, 2015). This amount of wasted food equals to one-year food production in China, and it could feed at least one billion people (Hanson et al., 2016). As countries producing large amounts of FLW, both China and the UK have put in place policies to address this. The most efficient way of controlling FLW is through avoidance; however, until all stakeholders' awareness of FLW prevention practices improves, it is necessary to find low-carbon and resource efficient disposal policies and practices that can reduce GHG emissions to the greatest extent.

A meta-analysis has been conducted to identify the existing LCA works related to FLW in both China and the UK, looking systematically at the selection of goals, functional units, and system boundaries of studies of FLW. In Scopus, search terms of 'LCA', 'Food', 'Food waste', and 'waste management' provides 19 Chinese papers and 17 UK papers. In all of these 36 papers, only 3 papers (all from the UK) considered FLW produced from all stages of food supply chain, and only 12 papers (9 from the UK, 3 from China) considered FLW's environmental burden from every stage of food supply chain. Hence, questions arise around the appropriateness of LCA studies that focus on post-consumer waste, as they naturally exclude these other substantial components of the FLW in the entire system, as well as any opportunities for improving management and synergy between these food system actors (Gathorne-Hardy et al., 2013).

Besides, a significant portion of waste generated in the food supply chain is not accounted for as FLW due to the definition gave by FAO, because it emphasised that only edible food's waste could be calculated as FLW. However, the determination of what is considered as edible food is subjective and arbitrary, which is varied among different countries and ethnicities. Chicken feet is a good example since it is delicious in China but be seen as non-edible in the UK. Nevertheless, despite the cultural differences, a large amount of chicken feet is produced every year in the UK. According to FAO, around 1.15 billion chickens were slaughtered in 2020, which means that there were at maximum 2.3 billion chicken feet produced (FAOSTAT, 2021). Consumed by people might be the most carbon-friendly way, but most chicken feet were disposed directly as waste, or made to pet snacks, which created waste GHG emissions and caused huge amounts of food loss. Hence, it is crucial to calculate chicken feet's GHG emissions during its supply chain by life cycle assessment, to find out the reasonable management methods (consumed, export, disposed, etc.) and meet the target of 2030 Courtauld Commitment and net zero carbon emissions.

A parametrized approach to regionalizing recycling life-cycle assessment inventories

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Arianne Provost-Savard [1], ***Robert Legros*** [2], ***Guillaume Majeau-Bettez*** [1]

1. CIRAIG, Polytechnique Montréal, 2. Polytechnique Montréal

Recycling processes show large technological differences between regions. For example, the efficiency of the recycling process, the energy and electricity mixes used, and the technologies employed for the treatment of rejects vary greatly according to technological and geographical factors. The treatment of recyclable waste has been globalised in the past years, and it is profitable for many countries to export waste to multiple international destinations (mostly countries with a high demand for raw materials) for recycling. This globalisation of recyclable waste flows, and the variability of recycling process parameters between regions, complexify the estimation of the environmental impacts and benefits of recycling. Existing life-cycle assessment (LCA) studies on recycling systems are underrepresenting developing countries, deficiently represent international trade flows, use unharmonized methodologies, and present inconsistent system boundaries and incompatible results. And yet, aiming to obtain detailed regionalized primary data to model the recycling system of every region of the world is an unattainable goal. Sectorial parametrization frameworks can be useful to represent many process variants in an efficient manner. This approach consists in selecting variable parameters that can be adapted to different geographical, technological, or temporal contexts. By varying the values of these parameters, it is possible to obtain life-cycle inventories (LCIs) that are specific to each context. The objective of this study is to develop an efficient and iterative approach for the parametrized generation of semi-automated LCIs that take into account technological and geographical variabilities in the recycling sector. An LCI regionalization framework is developed, to guide the collection and estimation of regionalized data on parameters applied to the recycling sector. The framework comprises three steps. The first step, *Scoping*, allows for a definition of system boundaries and a selection of the variable parameters. The second step, *Data Collection and Estimation*, consists in collecting and estimating data that minimize the geographical and technological uncertainty according to the pedigree matrix. Finally, the *Data Quality Evaluation* step allows for an assessment of the quality of the collected and estimated data for each parameter selected in the *Scoping* phase. The framework is used to build a parametrized tool that generates regionalized paper recycling LCAs. The tool is used to estimate the national impacts of paper recycling on climate change. Results range from 0.36 to 2.25 kg CO_2-Eq/kg of wastepaper recycled for graphic paper production, from 0.27 to 1.84 kg CO_2-Eq/kg of wastepaper recycled for newspaper production and from 0.28 to 1.68 kg CO_2-Eq/kg of wastepaper recycled for corrugated cardboard production. These results confirm the high variability of impacts according to the region where the recycling process is performed. The LCI regionalization framework developed in this study systematizes the integration and harmonization of primary data, geographical extrapolations, and technology models, so as to efficiently and iteratively reduce the uncertainties of global recycling LCAs due to data scarcity, and to provide a comprehensive geographical and technological data coverage of recycling processes. This research may ultimately guide legislation development towards more sustainable recycling practices.

Change in nitrogen inputs to the Chesapeake Bay watershed with the introduction of herbaceous feedstock

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Lucas de Lima Casseres dos Santos [1], ***Zia Uddin Md Chowdhury*** [1], ***Christine Costello*** [1]

1. The Pennsylvania State University

Introducing perennial grasses and winter biomass crops into agricultural landscapes can produce renewable energy and/or animal feed while improving water quality due to nutrient pollution reduction. Continuous cover and deep-rooted perennials are known to retain nutrients within agricultural fields. Grasses can be harvested and used to produce biogas through anaerobic digestion. At the same time, winter biomass crops could provide nutrition and substitute conventional animal feed such as corn, soy, and alfalfa. In this work, we updated and used a nutrient accounting model, the Commodity Specific Net Anthropogenic Phosphorous and Nitrogen Inputs model (CSNAPNI), to represent the change in net nitrogen inputs due to the introduction of grasses and winter biomass crops to act as best management practices, helping to reduce nutrient loads to the streams, and providing new economic opportunities through producing biogas within the Chesapeake Bay watershed (CBW), USA. CSNAPNI estimates the N & P input flows associated with 20 crop commodities and 19 livestock commodities and internally relates crops required for livestock diets, thus enabling N & P inventory development for a study region through a nutrient flow analysis perspective. We developed scenarios to approximate land use changes corresponding to changes to the crops produced; we then used CSNAPNI to estimate how that affect the nitrogent inputs in the CBW. In this analysis, cropland available for cultivation is not allowed to expand beyond current cropland use, and grasses will be assumed to replace one-tenth of the land currently used for corn production. In contrast, winter biomass crops were restricted to previously cultivated lands. Given that our scenarios reduce overall feed availability, we considered scenarios that held livestock production constant and those that reduced livestock production when grass displaced feed crops. This allows us to identify the implications in the regional nutrient balance and consequences for the livestock sector for producing biogas from grasses and winter biomass crops as another source of animal feed. Our preliminary results indicate that implementing the scenario would lead to a reduction in fertilizer use, which is one of the main drivers of nutrients to the region, and the production of corn that feeds the animals. We also observe that the reduction in the number of animals corresponding to the decrease in feed available would be below or equal to 11% in the grass replacement scenario. Besides the reduction in animal commodity production, that would still be bellow the national average of food lost or wasted which ranges from 17% to 30%. Ultimately, this assessment helps to evaluate the overall change in the nutrient load to the region associated with the commodities' production and draws attention to the benefits of introducing herbaceous feedstock as a strategy to improve the nutrient management of the Chesapeake Bay watershed.

TranSensusLCA: Developing a harmonized LCA approach for zero emission vehicles

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hazem Eltohamy [1]***, Bernhard Steubing*** [2]***, Jeroen Guinée*** [3]

1. Institute of Environmental Sciences (CML) - Universiteit Leiden, 2. CML Leiden, 3. Leiden University

The road transport system in Europe is rapidly transforming in response to climate change and resulting demand for more sustainable value chains. E-mobility and road electrification are one of the most apparent manifestations of EU efforts to achieve that. Nevertheless to guide this transition in a responsible a, a consensus on a life-cycle based tool for environmental assessment must be achieved. In TranSensusLCA EU Horizon project, a wide spectrum of influential European stakeholders in E-mobility sector have come together seeking such consensus. This spectrum ranges from academia and research, to industry which covers the entire value chains of Zero Emission Vehicles (ZEVs).

A lot of LCA on ZEVs and traction batteries was researched in literature, however subjectivity when it comes to critical modelling choices like choosing functional unit or allocation method hampers the utilization of these studies in further decision making. Therefore, there is a dire need for a single harmonized approach for applying LCA in E-mobility where all stakeholders can calculate, monitor, communicate, and make decisions starting from a common ground. The aspired harmonized approach is intended to be adopted by policy makers, standardization organizations as well which will eventually help create a momentum for a broader adoption with time.

The first main task of the project is a holistic review of previous and on-going work in the field (e.g. EU projects, guidelines, standards, scientific literature,..etc) in order to identify specific needs and gaps in current approaches. These identified issues are to be tackled in the next phase of the project by providing adequate methodological solutions. The outcomes of this review and the concluded methodological issues will be the focal point of the proposed poster.

Climate benefits of PLGA: A novel plastic based on atmospheric carbon

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Plastics are ubiquitous materials, used across a wide variety sectors and applications due to their low costs and versatile technical properties. Currently, about 99% of plastics are produced using fossil fuels, representing 6% of global oil demand and resulting 1.7 Gt CO_2-eq. of greenhouse gas (GHG) emissions per year. Under current trends, fossil-based plastics production and associated emissions may more than triple towards 2050. However, fulfilling the Paris Agreement goals would require major GHG emission reductions in all sectors and industries: in order to reduce and ultimately eliminate GHG emissions from plastics, an alternative feedstock to oil is required that is derived from atmospheric CO_2, either directly as direct air capture (DAC) or indirectly as biogenic carbon from sustainably sourced biomass.

This is what *Avantium*, a Dutch company in the field of sustainable plastics is aiming to achieve through its so-called VOLTA Technology. *Avantium* is working on producing polylactic-co-glycolic acid (PLGA) with a composition of 90% glycolic acid and 10% lactic acid, where all the glycolic acid is produced from CO_2 that could be sourced from DAC for example, and the lactic acid is fully bio-based. The VOLTA technology is currently at a demonstration stage, i.e., technology readiness level (TRL) 5. Original interest in PLGA stemmed from its suitability for biomedical applications because of its biodegradability and biocompatibility. Recent studies, however, showed that PLGA also has good water and oxygen barrier properties, making it suitable for a much wider range of applications. In packaging for example, PLGA could potentially substitute PET (polyethylene terephthalate), which is one of the main polymers used in packaging and constitutes 7% of the total plastics consumption in Europe.

Previous work has shown that polymers derived from CO_2 do not necessarily lead to lower overall GHG emissions, as this depends on the CO_2 source and capture technique, as well as on the end-of-life management of the plastic product. Here, we assess the greenhouse gas emissions of PLGA derived from CO_2 and biomass using prospective Life Cycle Assessment (LCA). We assess emissions for different possible CO_2 sources (e.g., biogenic carbon and DAC) and compare the GHG footprint of CO_2-derived PLGA with PET in packaging applications. Furthermore, we look at the potential climate benefits of PLGA from a wider, system perspective, considering underground storage of CO_2 as an alternative fate for CO_2 and accounting for the direct and indirect effects of replacing PET packaging with CO_2-based PLGA at scale, to evaluate the potential contribution of this novel plastic to climate change mitigation.

Prospective life cycle assessment to avoid unintended consequences of net-zero solutions and its challenges

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Climate change has led to specific carbon reduction targets including net-zero ones that are set to help in mitigating climate change by governments and organizations. This is not only to mitigate but also to meet the growing demands of the global population while ensuring practical progress and implementation. In line with those targets, alternative low-carbon energy technologies as well as those that capture carbon from the atmosphere are being hailed as practical solutions. For example, the UK government has set the ambitious plan of reaching net zero by 2050 which requires renewable energy, nuclear, hydrogen, and other low-carbon fuels to be accelerated significantly, while increasing the share of carbon capture and storage (Rt HonChris Skidmore, 2022).

These require innovation beyond existing technologies, i.e. developing emerging technologies. Although there is an optimistic view on the use of emerging technologies- as they may reduce energy use and subsequently CO_2 emissions across different sectors-, such technologies require different materials than established technologies, which can introduce different types of emissions up and down the supply chain. Such burdens should be carefully studied from the raw material requirements to the life cycle environmental impacts in order to avoid unintended consequences of the technologies in the future (Melin et al., 2021).

Therefore, from the early stage of technology development prospective life cycle assessment (pLCA) should be employed to assess the environmental impacts of emerging technologies (Bergerson et al., 2020). However, since the knowledge and information on emerging technologies are limited and scattered, major challenges exist when performing pLCA, e.g. consistency in modeling foreground systems, data availability, and uncertainty (Thonemann et al., 2020; van der Giesen et al., 2020). Here, we demonstrate some additional challenges by exploring emerging technologies for organizations using an example of a defense setting. The focus of this study is not on war-related operations, but rather looking into the decarbonizing the Defence estates and infrastructure systems -that are used by the military- using some emerging technologies such as Hydrogen, Carbon Capture, Geothermal, Electric Vehicles, and Solar Photovoltaics.

Most of the literature studies on pLCA focus on a single emerging technology development and its plausible sustainability impacts in the future. However, for governments and organizations to achieve net zero targets, they usually need to implement an array of emerging low-carbon energy technologies, some of which need to be employed in parallel e.g. emerging low-carbon energy generation and energy storage systems. This adds further complications and challenges to the pLCA as economics, environment and variability related issues. Firstly, different emerging technologies have different temporal horizons in reaching commercial maturity and respected market and technology readiness level. Second, such assessments are complicated as finding the most optimal combination of different emerging technologies needs to balance the pros and cons of different technologies in terms of different sustainability impacts which makes the problem a kind of multi-criteria problem that involves a large number of variables (Torkayesh et al., 2022). Third, large deployment of emerging technologies would also imply some consequences on the marginal markets and that needs further consideration. Therefore, it is of great importance to assess emerging technologies on wider economic scales and consider the potential market share of them. Finally, there are some technology and market interventions that also need to be considered. All these challenges need proper remedies and further research when performing pLCA.

Leading the transion of the european automotive supply chain towards a circular future - TREASURE

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Abel Ortego [1], ***Paolo Rosa*** [2], ***Alicia Valero*** [1], ***Ricardo Magdalena*** [1], ***Samuel Alcoceba*** [1]

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TREASURE (leading the TRansion of the European Automotive SUpply chain towards a circulaR futurE) is an European project funded by the European Union's Horizon 2020 research and innovation programme.

TREASURE wants to support the transition of the automotive sector towards Circular Economy (CE) trying to fill in the existing information gap among automotive actors, both at design and EoL stage.

To this aim, a scenario analysis simulation tool dedicated to car electronics is being developed with a set of dedicated industrial demonstration actions. The scenario analysis simulation tool will have a multiple perspective. From one side, the TREASURE solution can assist both car parts suppliers and carmakers in assessing their design decisions in terms of circularity level, also considering the effects of their decisions on EoL processes (e.g. on car dismantlers and shredders operational performances and advanced metallurgical recycling processes). Viceversa, car dismantlers and shredders could benefit from the TREASURE solution by knowing about new design features of cars to be recycled in order to optimize their processes.

From another side, the TREASURE project acts as an information hub, by exploiting data stored in the EU raw material information system (RMIS) database. These data will be directly exploited by TREASURE to continuously monitor CE performances through a dedicated circular economy performance assessment (CEPA) methodology.

TREASURE consortium is coordinated by Politecnico di Milano and it is formed by a group of 15 organizations from 7 European countries (Italy, Netherland, Spain, Switzerland, Estonia, Latvia, France), which complement each other in terms of background knowledge, technical competence, capability of new knowledge creation and business and market experience where the project results can be readily exploited.

This poster is intended to present the results obtained by the project during the first 18 months as well as the next steps to be taken.

Unveiling the nexus profile of embodied water–energy–carbon–value flows of the Yellow River Basin in China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Lei Cheng [1], ***Haoge Xu*** [1], ***Jinping Tian*** [1], ***Lyujun Chen*** [1]
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Water resource deficiency, energy shortage, and intensive carbon dioxide (CO_2) emissions are the three vital environmental issues in the context of global climate change(X. C. Wang, Jiang et al., 2021). These issues are closely intertwined and call for a holistic countermeasure; thus, exploring their complex relationship from multiple dimensions is essential for regional and global sustainability (X. C. Wang, Klemeš et al., 2021). For the integrated management of diverse environmental factors, nexus thinking — a systems-based perspective — has been widely employed to address the complex interactions among multiple resource systems (Albrecht et al., 2018).

This study takes China's Yellow River case, which is known as China's Mother River and "Energy Basin," to unveil the nexus profile of embodied water-energy-carbon (WEC) and added-value flows of the Yellow River Basin (YRB) in China. The YRB is a core region for achieving China's energy transition and "dual carbon" (i.e., CO_2 peaking and carbon neutrality) targets (Jiang et al., 2021). Meanwhile, the YRB has witnessed substantial challenges, such as frequent floods, soil erosion, and water shortages. Nevertheless, previous studies on the YRB have focused on the carbon or water footprint flows embodied in the regional trade(An et al., 2021; Liu et al., 2021; S. Wang et al., 2016; Yin J et al., 2016; Yuan et al., 2022), minimal research explores the WEC and added-value nexus efficiency of the YRB from a holistic perspective.

Therefore, we constructed a nexus framework to analyze the embodied WEC, and value flows in the nine provinces of the YRB and all 31 provinces in China based on the multiregional input–output model (MRIO). Three dimensions (space, sectors, and factors) depict the WEC and value nexus patterns. The embodied WEC coefficients from the consumption side evince significant differences from the direct coefficients. The YRB has more significant positive correlations among embodied water, energy, carbon, and value-added than at the national level. From a spatial view, the YRB presents a pattern of a water and energy footprint net outflow and a carbon footprint and value-added net inflow. In addition, the profiles of different provinces are carefully explored, and the imbalance of economic development among the nine provinces is aggravated, particularly for those provinces with abundant energy resources. Moreover, in the sectoral dimension, hotspot sectors with high energy and water consumption and low value-added include the energy production and supply industry, the mining industry, and the petrochemical industry in the basin. These sectors are the key to the YRB's low-carbon transformation and sustainable development.

The study systematically explains how embodied WEC interacts with concomitant economic activities within and beyond the YRB, uncovering that the YRB benefits from regional trade but suffers environmental losses. The nexus framework proposed in this study, considering both multi-environmental factors and economic factors for multi-region, could be a general framework for other regions and related water-energy extended nexus analysis, as well as the trade-off analysis between environmental and economic indicators. Meantime, the implementation paths of carbon offset policies among partner regions and the sustainable water management policy recommendations that integrate water, energy, carbon, and other factors concluded from this study have reference value for other regions' sustainable development in China and the rest of the world.

A life cycle perspective of the second-generation polylactic acid and its integration with chemical recycling

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ricardo Rebolledo-Leiva [1], *Dimitrios Ladakis* [2], *Sofia-Maria Ioannidou* [2], *Apostolis Koutinas* [2], *SARA LAGO OLVEIRA* [3], *María Teresa Moreira* [1], *Sara González-García* [1]

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The climate crisis demands moving from petrochemical to bio-based products to reduce the environmental consequences on the planet. Plastic pollution is one of the biggest worldwide threats, and its production is expected to still grow to accomplish the rising food demand. Bioplastics appear as a renewable source that avoids fossil-resources consumption with similar characteristics to their fossil counterparts. From them, polylactic acid (PLA) is one of the most widely used biopolymers, due to its mechanical properties and renewable origin, to produce compostable bio-based plastic for food packaging. This work aims to estimate the potential environmental feasibility of a second-generation (2G) PLA production based on wheat straw; and the role that integration with a chemical recycling plant can play in the environmental performance of a circular bio-product at an early stage of design. The attributional Life Cycle Assessment methodology, through a cradle-to-grave boundary, was performed following the ISO 14040-14044 guidelines. The wheat cultivation stage is carried out in Apulia, Italy, and an economic allocation was used to distribute the environmental burdens between wheat grain and straw. An annual production capacity of 40,000 tons of PLA and 40,000 tons of lactic acid (LA) recycled were considered for the biorefinery and the recycling plants, respectively. Thus, the amount of LA that the biorefinery could obtain from the recycling plant is equivalent to 80% of its demand. The PLA biorefinery platform consists of different stages such as pre-treatment of straw, lactic acid production, and PLA production. The chemical recycling plant starts with a pre-treatment section with manual sorting, washing, and shredding of the PLA waste. Then, depolymerisation, separation, and concentration processes were performed. The separation unit corresponds to a centrifugation process to recover unreacted PLA, which is sent back to the depolymerisation reactor. After that, the lactic acid solution is concentrated at 99%. Impact categories such as Global Warming, Eutrophication, Eco-toxicity, Water Consumption, and Land Use, among others, were estimated using the ReCiPe v1.1 (H) impact method and Simapro® 9.1 software. Environmental burdens are expressed in terms of the main products in each platform; thus, the functional units were 1 kg of PLA produced in the biorefinery plant and 1 kg of lactic acid in the recycling plant. Results show that lactic acid production was the main contributor to the environmental burdens of the biorefinery due to the wheat straw pre-treatment process and the recovery of pure L-lactic acid. In the chemical recycling plant, depolymerisation was the main environmental hotspot. The integration of LA recycled leads to a significant reduction of PLA burdens, ranging from 1.42 to 0.45 kg CO_2eq (70%) in the Global Warming category, as well as in the Water Consumption category from 0.12 to 0.03 m^3 (75%). Only the Land Use category grew its burdens by about 21%, due to the energy demand supplied by a cogeneration system. Thus, recycling strategies can support the promotion of bioeconomy models to address plastic challenges.

Acknowledgments

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LIFE CYCLE ASSESSMENT OF THREE NOVEL TECHNIQUES FOR REJUVENATING "OLD PVC": REMADYL CASE STUDY, CHALLENGES AND BENEFITS

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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With the evolution of human beings, it has become increasingly difficult for the environment to be sustainable. Plastics have been used by individuals and organizations over the years for different purposes due to their durability, cost-effectiveness, and lightweight. Plastic can be considered extremely useful but can be highly dangerous for the environment and living beings. PVC is one of the most commonly used forms of plastic and Until 2021, global demand for PVC increased by 3.2%. It is a polymer that is used to produce a wide range of short- or long-life products. However, due to the increase in its use in recent years, the amount of used PVC items entering the waste stream has gradually increased contributing to toxicity for human health and to the environment. The production, use, and disposal of polyvinyl chloride (PVC) have environmental consequences that range from global warming to decreased air quality. In this context, recycling plastic waste might be an effective solution to the problem of plastic pollution. Today, PVC recycling is done through either a mechanical or chemical method, however, one of the most persistent problems in PVC recycling is the removal of Legacy Substances (LS), such as lead and DEHP. In this work, we investigate from the environmental performances by means Life Cycle methodology (LCA) of three different innovative technologies for PVC recycling. The technologies developed within an H2020 research project framework, named REMADYL, are: (i) Extraction of plasticizer from soft PVC with supercritical CO_2 ; (ii) Extraction of lead with (NA)DES; (iii) Extraction of lead with LDH. The results show that CO_2eq. life cycle emissions ranging from 1.8 up to 7.45 kgCO_2eq. in the case of technology (i), 0.1 up to 73.9 kgCO_2eq for (ii) and 0.65 up to 0.78 kgCO_2eq for (iii).

Methodology development for decision on the allocation factor considering recycling effect

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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As one big contributor to greenhouse gas (GHG) emissions, it is important to reduce the GHG emissions in the material manufacturing industries. Life cycle assessment is an acknowledged tool to select the material which can achieve the lowest life cycle GHG emissions of a product. Material recycling can reduce GHG emissions, especially of metals significantly. Different materials can have different recyclability. Quantifying the recycling effect of materials is a remaining issue concerning system boundaries in the life cycle inventory analysis, which is dealt with different recycling approaches. According to a review, it is found there was a lack of common procedures to select a recycling approach considering the recycling effect of materials. Considering the application of recycling approaches in practice, based on the discussion on the three typical recycling approaches – cut-off, partitioning, and avoided burden approach, it is found that the avoided burden approach is an empirical approach considering the recycling effect. However, there were a few methodologies on the decision of allocation factor A, which is essential for allocation of the avoided burden in this approach. One pioneering market-based methodology was proposed but it is thought that temporal fluctuation of the market condition could impede its practice. Therefore, the objective of this work is to develop a solid methodology for decision on the allocation factor.

In the avoided burden approach, there are three typical allocation methods – waste mining, end-of-life, and 50-50 method, which corresponds to the value of 0, 1, and 0.5 of the allocation factor A. In this study, a solid methodology for the selection of three allocation methods is developed based on the direct restrictions during recycling. In theory, a general fundamental rule for the selection of the allocation methods is proposed. To decide the allocation methods, the supply restriction and quality restriction should be investigated with the effort from either the supply side or the demand side can enhance recycling. For the application of the methodology, a definition of the same material group is proposed to investigate the supply restriction. It is found that the material class according to the Taxonomy of the Materials Kingdom can be referred to define the same material group. It is discovered that the material flow analysis can check the mass balance of the potential supply and potential demand of the secondary resources for an investigation into the supply restriction. The knowledge of material engineering is found to be able to investigate the quality restriction and the technologies in the supply and/or demand side to avoid the restriction in recycling. In particular, how to investigate the supply restriction when there are different grades of materials in a material class is added to the general methodology. The case of wrought aluminum alloys and cast aluminum alloys are taken as an example for demonstration. So far, the whole methodology is developed and finally presented in the form of a decision tree.

In conclusion, this study develops a solid methodology to decide the allocation factor A for the avoided burden directly based on restrictions during material recycling. For the first time, the knowledge of industrial ecology is tried to be combined with that of materials engineering. It manages to be a practical support reference for materials selection based on the life cycle inventory analysis with careful consideration of the recycling effect.

Global assessment of plate food waste in schools

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

lei feng [1], ***Yi Yang*** [1]

1. Chongqing University

Agri-food systems are a major diver of many global environmental problems from climate change, water scarcity and pollution, to biodiversity loss. Roughly one-third of global food is lost or wasted annually and thus reducing food waste has been proposed as an effective method for tackling agri-food sustainability challenges and ensuring global food security. Reducing food waste requires mostly behavioral change on the part of consumers, and yet behavioral change is difficult once lifestyle habits have already been formed. On the other hand, good habits formed during one's childhood can persist through adulthood, underscoring the need for early interventions in the case of addressing wasteful behaviors. In this talk, we present the first global assessment of plate food waste in schools with the aim of understanding the magnitude of student food waste, what drives it, and what is effective at prevention and mitigation, as well as its life-cycle environmental implications. Our results reveal that school plate waste varies widely across countries (by nearly 10-fold), and that student food waste rates seem to be positively correlated with country income levels, suggesting that as a country becomes richer, it tends to waste more food. This represents a worrying sign for future food waste trajectories, because lower-income countries, as they continue to develop and their population continues to grow, will be the main driver of the increase in food demand. Data on lower-income countries are still limited and more field research in these countries are urgently needed to better understand student food waste in those countries. Among high-income countries, Japan stands out as a "outlier" with much lower food waste amount and rate than other high-income countries, due in part to the success of their food education programs. We estimate that 134 Mha of cropland, equivalent to [J.C.1] the entire area of arable land in the US, and 682 Mt CO_2e of greenhouse gas (GHG) emissions, twice the total national GHG emissions of the UK in 2020, are embedded in student plate waste on a global scale. Additionally, we summarize the drivers and effective interventions of school food waste unearthed in the literature. Based partly on these insights, we propose a comprehensive food education framework that integrates the collaborations among stakeholders across different scales. This framework could help enrich existing food and nutrition education approaches. If we have any success of winning the war against food waste, not only should we alter our behaviors, we must also ensure our future generations grow up wasting much less food than we did.

Assessing the environmental performance of a containerized vertical farm: Case study from IKEA

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Vertical farms (VF) have expanded rapidly in recent years as an approach to secure resilient food provisioning worldwide. With the expansion, there has been increased criticism of the sustainability of the systems, due in part to claims from the media and producers. However, there are few sustainability assessments of the implications that VFs have throughout their life cycle.

This study aims to provide an environmental life cycle assessment of a case study vertical farm located in Sweden. In particular, this study was based on a container-based vertical farm employed by IKEA to provide the store cafeteria with fresh salad. To assess the environmental performance of this system, a life cycle assessment (LCA) was conducted to assess the overall impact of producing 1 kg of salad supplied to the cafeteria. Furthermore, the LCA was conducted to highlight important ‘hot-spots’ of the production in order to identify improvement options and compare with conventional sourcing.

The GHG emissions impact were roughly 1.2 kg CO2-eq. per kg of lettuce produced. The largest impacting processes were the energy demand for the light-emitting diodes (LEDs) and the ventilation system. Energy demand also contributed largely to all other impact categories assessed. The infrastructure, i.e. container and all associated machinery and technology required, also contribute to over 15% of the overall impact, showing its importance for vertical farms. The results were also found to be sensitive to the choice of life cycle inventory data for the growing media and electricity mix. Further scenarios to improve the environmental performance were also conducted. These included replacing peat with coconut coir, in addition to employing circular nutrient solutions from farm and cafeteria wastes. These mitigation options showed potential to reduce the GHG emissions. Assessments and comparisons to conventionally imported lettuce were also conducted based on input from the cafeteria for sourcing, showing that the vertical farm had emissions similar or lower than those imported lettuce varieties with similar or improved quality.

In conclusion, the results suggest that the vertical farm, despite the high energy demand, can provide lettuce to the store with comparable emissions and quality compared with imported lettuce.The results provide novel insights for the controlled environment agriculture field, vertical farming producers and retailers of the environmental performance of vertical farming container solutions, providing empirical evidence of their sustainability and viability for food provisioning locally.

Assessing the environmental implications of sustainable and circular public procurement food

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Recent studies have addressed the use of sustainable public procurement (SPP) as an efficient tool to improve the sustainability of the food system, as it is one of few regulatory instruments to influence sustainability along the supply chain. Despite the many claims of how sustainable certain procurement practices may be for food, few studies have assessed the implications that different interventions have on the sustainability of SPP of food. This study has aimed to understand and analyze the environmental implications of the SPP of food from the Jämtland region in Sweden. This is done employing an environmental-spend analysis (ESA); an approach that combines purchasing data and life cycle analysis (LCA). A baseline year from 2020 procurement data was used for the study. We assessed the baseline, and furthermore, scenarios are included to improve both sustainability and circularity of food procurement. These include increasing organic and local foods, reducing certain food types (meat), and expanding others. In addition, circularity is assessed through reducing food wastes, focusing on packaging, and new waste handling approaches.

Results from the assessments suggest that targets for organic foods may not entirely lead to large GHG emissions reductions, which may be counterintuitive to the narratives used by local politicians. Instead, expanding the use of regional foods, e.g. local wild-game meat, reducing food waste, and valorizing waste streams can greatly reduce environmental impacts from the food procured for the region. Local and organic foods also largely reduce potential biodiversity damage and toxicity. These results suggest that a focus limited to climate impacts and share of organic foods may not be holistic to address sustainability for food systems. The results also provide insights to procurement officers on focus areas to promote more sustainable procurement processes and for increased LCA data to ensure that better decisions can be made without shifting burdens.

Integrating black soldier fly decentralised facilities into the food waste treatment infrastructure system: Potential in Megacity Beijing

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Haoran Qiao [1], ***Xin Tong*** [1]
1. *Peking University*

The proper treatment of food waste is a key part of the solution to urban waste overload and sustainable development. Insect bioconversion like black soldier fly larvae(BSFL) is widely considered to be the optimal food waste treatment method because of its low input, high output and low pollution advantages. In this study, we estimated the total amount of food waste generated in Beijing in a year, and found that the corresponding capacity of food waste treatment facilities was far from adequate. To solve this problem, a common standard model was presented, which is a community food waste treatment station using BSFL. We consider it as an decentralized infrastructure unit, and then propose an infrastructure treatment system consisting of both centralized and decentralized facilities. We analyze how Beijing can allocate between the two types of facilities to maximize their effectiveness. Preliminary conclusions suggest that Beijing has a large potential for the use of BSFL, and BSFL are more appropriate in the densely populated central areas of Beijing. The novelty of this study is Beijing as a case practice, from an infrastructural perspective analyzing the potential of BSFL bioconversion facilities in large cities.

The societal and environmental opportunities of reducing sugar consumption

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Sugar overconsumption is associated with multiple diet-related diseases such as diabetes and obesity while driving a variety of environmental pressures. The environmental impacts of sugar consumption have typically received less focus due to its perceived low-impacts per calorie compared to other foods. Some countries such as the UK and Mexico have introduced sugar-sweetened taxation to reduce the sugar consumption, however, other countries such as Israel have cancelled sweetened beverage taxes that threaten public health.

To help policy-makers fully understand the societal and environmental opportunities of reducing sugar consumption, we explore the use of these saved sugars in the production of synthetic protein, biofuels, or bioplastics or replacement with other food items (e.g., vegetables, and fruits). We also explore the opportunity for carbon sequestration and biodiversity protection of simply sparing the land saved from reductions in sugar intake.

We outline current policies for sugar regulation and highlight the need for a joined-up approach across environmental, economic, health, and land policy to provide a smoother transition pathway for the sugar industry, reducing tensions while harnessing environmental and public health opportunities.

Future greenhouse gas emissions of sodium ion batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Monday, 3rd July - 15:45: LCA case studies 3 (C0.06 KOG)

Shan Zhang [1], ***Åke Nordberg*** [1]

1. *Swedish University of Agricultural Sciences*

Battery technologies play an vital role in the transition to a fossil-free society. Sodium-ion batteries (SIBs) are attracting significant attention as promising energy storage alternatives to lithium-ion batteries, due to abundant reserves and low cost of sodium. The environmental impacts of SIBs have been studied by several life cycle assessment studies. However, there is a lack of study to analysis future environmental impacts of SIBs, with considering the changes in the background system in the future. This study aims to conduct a prospective life cycle assessment to estimate the future GHG emissions of cell production in 2030, 2040 and 2050. Three SIB technologies were studied: layered oxide cathode with hard carbon (HC) anode; polyatomic anion cathode with HC anode; and Prussian white cathode with HC anode. The future background system was molded using the integrated assessment model REMIND, in combination with the Shared Socio-Economic Pathway 2 scenario. To facilitate a fair comparison, all three battery cells were modeled as a classic 18650 form, using a bottom-up approach. The best available data (latest data) was used to model the cell dimension and battery cell production system. The focus of the study was on cell production, therefore, a cradle-to-gate system boundary was applied. A functional unit of 1 kWh cell capacity was used. To gain a better understanding of the environmental performance of SIBs, results were compared to that of lithium-ion batteries. In sensitivity analysis, the effect of different HC production methods on the results was analyzed.

Multi-model assessments for anticipated agricultural non-CO2 footprints reduction driven by the demand of non-food commodities

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Haoran Zhang [1], ***Zhifu Mi*** [1]

1. *University College London*

Agricultural non-CO_2 emissions represent over 12% of total anthropogenic GHG emissions and have a key role in achieving the 1.5 ℃ climate target. With agriculture characterized as essential sector in global and region supply chains, the air pollution and GHGs emissions embodied in the final consumption and trade of food commodities have been much discussed by previous studies. However, a quantity of agricultural goods is not directly used by final consumption (e.g. households) but intermediately by the industry as primary goods. Standard MRIO analysis is accurate for assessing the impacts of final goods directly consumed by final consumers. It is difficult to capture the impacts of these intermediately use of agricultural goods by non-food commodities. As these non-food commodities are directly facing consumers, the emissions of agricultural sectors associated with them are significant and yet to be characterized. Here, we used a cutting-edge extended-products MRIO method to assess the non-CO_2 emissions along the global agricultural goods value chain, especially to capture the impacts associated with the non-food commodities. Participating in multi global MRIO databases (e.g. EXIOBASE, EORA, EMERGING, GTAP and WIOD), we provide a multi-model assessments and statistical estimation and explanation for comprehensive exhibition. Our results could help to understand the special responsibility of non-food commodities and ensure a clean agricultural supply chain.

Food demands transition in China's ageing society challenges planetary boundary

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Qingling Wang [1], ***Han Zhang*** [1], ***Heran Zheng*** [2]

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[Motivation] Food systems place so large burdens on the environment that several impacts have reaching or exceeding the planetary boundaries (PBs). China's food system has already made great contributions to food-related environment impacts, while the country is experiencing rapid ageing. Older people exhibit specificity in their dietary expenditure preferences due to physiological changes. Previous studies have drawn contradictory conclusions on the relationship between food systems and planetary boundaries, yet a thorough understanding of how China's dietary structure and demanded food quantities evolve with ageing and whether diet-driven environmental footprints transcend global PBs, is still missing. To sum, this paper attempts to provide a national assessment of the diet-driven environmental impacts of ageing in China, then comparing them global PBs.
[Methods and data] To reveal the dietary expenditure patterns by age group, we use individual-level dietary survey data and construct a quadratic almost ideal demand system (QUAIDS) model. After that, total food demand based on China population ageing scenario is estimated with reference to the Shared Socio-economic Pathway (SSP) framework until 2050. For further assessment of diet-driven environmental impacts, we take a consumption-based approach in which dietary transition in one country incorporates the environmental impacts both locally (domestically produced food) and globally (imported food). A multi-regional, environmentally extended, input-output (MRIO) model and EXIOBASE database are thus employed. Subsequently, the diet-driven footprints and corresponding PBs are compared to identify future pressure on the environmental system caused by ageing. Here we put the spotlight on greenhouse gas (GHG) emissions, eutrophication and land use because these are highly associated with food systems and have impacts reaching or exceeding PBs.
[Results] Firstly, we find that expenditure elasticities for all age groups and food types are positive, while the aged over 60 act out significant differences in dietary expenditure patterns than those of other groups. Secondly, under the assumption of the trade matrix and emission intensity being constant in 2020, three diet-driven footprints show similarity between-group heterogeneity, i.e. total footprints of the elderly will exceed that of those aged 20-40 in 2029 and those aged 40-60 in 2034. Thirdly, the aged is the main contributor to the increase in all three footprints in 2050 relative to 2020. Threats posed by China's food demand to the downscaled national PB vary by time, country and footprint type. As ageing evolves, China's food-related footprints will not exceed the global PB, but eutrophication and land use will transgress national PBs in both 2020 and 2050. Finally, the top 3 countries in terms of challenge to GHG PB by 2050 are Luxembourg (16.3%), the Netherlands (9.7%), and the Republic of Korea (9.7%). The top 3 countries in terms of challenge to eutrophication PB are Denmark (37.9%), Netherlands (34.9%) and Luxembourg (32.6%). The top 3 countries or regions in terms of challenge to land use PB are RoW Asia and Pacific 61.37%, RoW America 41.3%, and Australia 29.3%.

Net Positive LCA Beyond Negative Realms

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Delwyn Jones [1], ***Mathilde Vlieg*** [2], ***David Baggs*** [3], ***Shloka Ashar*** [4], ***Olivia Manzart*** [4]

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Problem centric methods need the depth of field to bring solutions into focus. Finding solutions for sustainable development requires modelling the regeneration and recovery of safe accessible operating space within planetary boundaries. The UN Nature Positive Program provides a global impetus for industrial ecology and circular economy stakeholders to reach zero climate and biodiversity loss and beyond to net-positive gains. To assess nature-positive refitting of the world's vast urban and industry systems life cycle impact assessment (LCIA) must evolve beyond modelling damages and loss.

Life cycle assessment (LCA) literature rarely considers increased ecological carrying capacity of built and urban systems addressed in other fields such as Architecture. So life cycle benefit assessment (LCBA) was developed to supplement LCIA. Approaches to quantify climate and supply security, human wellness and ecosystem replenishment reach beyond LCIA's negative range from damages to zero loss.

Together both may quantify ecologically sustainable development. Preindustrial periods offer regeneration benchmarks for ecosystem service equivalents for comparable territory e.g species richness and ground water retention. LCBA metrics cover positive to zero then net-positive environmental gain benchmarks in prior or contemporary safe operating space within planetary boundaries to quantify the following.

Human adjusted life years (HALY) from avoided environmentally induced illness and disability is modelled/m^2 area per annum per capita in benefit layers including:

- Indoor Oxygen: kg oxygen generation with carcinogen sequestration
- Low Allergen Air: kg sequestered dust, inorganics and allergens
- Climate Braking: $kgCO_{2e20}$ sequestered climate with less damage
- Safe Water: m^3 rain, potable water & clean toxin-free effluent
- Food Access: kJ secure homes

Positive ecosystem refill (PERF) from new species, habitat, biodiversity, urban, catchment fractions is measured/m^2 area fraction per annum in benefit layers including:

- Safe Space: capture pollutants to protect corridors and habitat
- Bio-Stock: replenish terrestrial aquatic biodiversity
- Urban Bounty: area converted to full natural carrying capacity
- Secure Climate: soil & biomass sequester CO_{2e} & generate O_2

Supply energy & resource viability (SERV) from renewable and recyclable resources is modelled in MJ/m^2pa in benefit layers including:

- Water: replenish locally accessible reservoirs
- Supply: replenish locally accessible resources
- Fuel: enhanced catchment of renewable fuels
- Mineral: regeneration of finite reserves & stocks
- Reserve: regenerated stocks of scare reserves
- Food: reliance on local Organic food pp

Considering safe operating space for humanity, positive LCA theory and methodology uptake facilitates envisioning earth system goals, gaps and gains. Modelling LCIA together with LCBA can yield balanced LCA which is a vital key to quantify net-gains in wellness, reparation and regeneration.

Cradle to grave LCIA +LCBA results from certified Environmental Product Declarations (EPD) are discussed. Residential high rise garbage chute EPD results show gains in space and resource recovery over 60 years use. Overall positive gains far outweigh losses. Net positive outcomes were quantified for wellness, healthy airsheds, climate braking, water clarification, habitat recovery as well as water, energy and mineral recovery outcomes The work concludes that damage-focused LCA excludes net-positive benefits. Sustainable development needs positive concepts, methods and metrics to assess benefits and benchmarks. Balanced LCA is vital to envisage and estimate environmental gains.

Its uptake can help practitioners to sight, model and measure system gaps, gains and goals in industrial ecology and circular economy systems worldwide. The world's first certified nature-positive ecolabeling system and EN15804 compliant EPD platform uses LCBA.

Global spread of water scarcity risk through trade

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Xi Chen [1]***, Bu Zhao*** [2]***, Chenyang Shuai*** [3]***, Ming Xu*** [4]

***1.** Southwest University,* ***2.** University of Michigan,* ***3.** Chongqing University,* ***4.** Tsinghua University*

Water scarcity is becoming a significant obstacle to the sustainable development of human society. The economic impact of water scarcity is referred to as water scarcity risk (WSR), which constitutes local water scarcity risk (LWSR, local economic output loss in water-using sectors due to water scarcity) and virtual water scarcity risk (VWSR, the spread of LWSR from upstream producer to the downstream purchaser through trade systems). However, the traditional water stress index used in the existing WSR assessment research is limited in its accuracy and descriptiveness. To address these limitations, we have quantified LWSR by taking into account environmental flow requirements, water intensity, and economic output. Additionally, we have evaluated VWSR using a global multi-regional input-output model. Results indicate that in 2016, the direct impact of local water scarcity on the global economy was approximately $1.2 trillion, and the indirect impact was approximately $1.5 trillion. Emerging markets and developing economies imported $491 billion in VWSR from advanced economies, compared to $33 billion from EMDEs to AEs. This highlights the need for EMDEs to reduce their dependence on AEs. Our study also identifies critical economy-sectors where local water scarcity has a significant impact on other sectors through trade. For example, the *Electrical and Machinery* and *Financial Intermediation and Business Activities* sectors in Singapore and the *Agriculture sector* in China and India are critical for the resilience of the global trade system to VWSR. Decision-makers should focus on these “hotspots” to mitigate VWSR transmission. We also identify top importers of VWSRs at the economy-sector level, including the *Food & Beverages* sector in India and China, and the *Electrical and Machinery* and *Construction* sectors in China. Decision-makers in these sectors should diversify their upstream suppliers. Our findings help lay the foundation for nations to develop strategies for mitigating WSR.

Pattern of carbon peaking for China's urban agglomerations

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Chengqi Xia [1] ***, Heran Zheng*** [2] ***, Jing Meng*** [2]

1. *Tsinghua University,* ***2.*** *University College London*

City-level carbon mitigation effort is an indispensable to achieve climate target, particularly carbon peak for China. However, the most carbon mitigation efforts focus on individual cities, and overlook the spillover effects of intercity supply chains. The omission raises the question of whether the peak is achieved directly by their own efforts or indirectly through the efforts of others through supply chains. Urban agglomerations where cities are the most economically linked become a crucial unit to understand the carbon peaking. Here, we present the evolution of carbon footprints of China's 16 urban agglomerations (199 cities) from 2012 to 2017, and identify the pattern of carbon emissions trend.

We found that four urban agglomerations recovered while six carbon footprints rose, reaching a peak in six urban agglomerations. After disassembling the driving force of carbon footprint, we found carbon peak pattern of Beijing-Tianjin-Hebei is driven by consumption structure, and peak patterns of Shandong Peninsula and Chengyu are driven by production factors, their carbon peak models are role models, and manufacturing and construction are usually major emission reduction sectors. Three urban agglomerations, which are Liaozhongnan, Harbin-Changchun, and Taiyuan, reached carbon peak were resulted of population reduction and per capita consumption decline, and their emission reduction are free riding through the supply chain. Non-carbon peak urban agglomeration should learn from role model experience, and take full advantage of local advantages, form industrial cluster effect, and fully cooperate within urban agglomeration to carry out low-carbon transformation.

Stocks and flows analysis of settlements in the Greater Oslo: an investigation of Resource Efficiency Strategies

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Lola Rousseau [1]***, Fabio Carrer*** [1]***, Jan Sandstad Næss*** [1]***, Edgar Hertwich*** [1]

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In 2021, Oslo and Viken, the two counties with the largest populations in Norway, were responsible for around a third of direct road transport greenhouse gas (GHG) emissions as reported by the Norwegian Environment Agency. Mobility by bus and passenger cars represent nearly 50% of these emissions. However, the inhabitants of these two neighbouring counties seem to present different mobility patterns: direct GHG emissions of mobility in Oslo were around 0.38 tCO2eq/capita in 2021 while in Viken, these were around 0.68 tCO2eq/capita.

In our work, we aim to understand the current mobility patterns in these two counties and how resource efficiency measures could target the GHG emissions from mobility (direct but also indirect emissions). Our analysis is informed by the Open Dynamic Material Systems Model for the Resource Efficiency-Climate Change Nexus (ODYM-RECC), an open-source community tool, used to evaluate material efficiency strategies in passenger vehicles and residential buildings at country scale. We are expanding and applying the framework to Oslo and Viken. While an analysis at the country scale gives some perspectives on the potential material use and GHG emissions pathways a country as a whole is undertaking, we believe that investigations on a local scale have a key role to play in understanding spatial differences of mobility and provide further insights of urban services provision and development.
Our work is in three folds:

- Expanding the ODYM-RECC model to include new products such as transport infrastructure.
- Data collection and processing related to mobility and built environment in Oslo and Viken.
- Scenarios analysis of the counties.

The expected result from this work is an ODYM-RECC framework allowing for resource efficiency strategies applied to the Oslo and Viken counties. We are also spatially visualizing the results to provide an understanding of the spatial distribution of the built environment components.

Can circular strategies contribute to sustainable food production in cities? The case of nutrients circulation in a metropolitan area for urban agriculture.

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***gara villalba* [1], *Angelica Mendoza Beltran* [2], *Susana Toboso* [1], *Juan David Arosemena* [1]**

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Cities will require several transformations to become more resilient, sustainable and multifunctional systems, especially in terms of provision of food. In this study, we attempt to determine to what extent circular strategies can help in the sustainability of future food production of metropolitan areas. In particular we focus on nutrient circulation strategies and further assess theoretical transition scenarios for urban agriculture (UA) using prospective-regionalized LCA integrating knowledge from previous studies on urban land use, nutrients recovery from municipal sources, regionalized LCA of UA and prospective LCA. We apply this approach to the Metropolitan Area of Barcelona (AMB) to evaluate the direct and indirect impacts such as climate change and eutrophication of potential future expansion of urban agriculture as proposed by the urban master plan using the functional unit of yearly total crop production. The various nutrient circularity scenarios proposed include the use of struvite from waste water treatment plants and compost from domestic organic waste. Results show that in light of future resource restrictions, circular nutrient strategies will have an increasingly important role in cities to supply nutrients for urban crop production while reducing impacts associated to UA. However, they need to be considered in terms of their life cycle as alternatives to mineral sources of nutrients and as a reduction in waste management to see the environmental benefits of UA.

Environmental sustainability of oyster production in Portugal

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Paula Quinteiro [1], ***Ana Cláudia Dias*** [1]

1. *University of Aveiro*

Seafood has a relevant role in meeting food demand while also contributing to climate change mitigation as it typically presents lower greenhouse gas emissions than most land-based foods.
Oysters production has increased rapidly in the last years and nowadays represents a relevant portion of the global aquaculture production dominated by China, which accounted for around 83% of global production. In Portugal, it represents about 25 % (by volume) of aquaculture production. Oysters produced in Portugal are exported to European markets such as France and Belgium, thus not being a ‘short-chain typology’, which would imply proximity between producers and consumers in order to mitigate environmental impacts. In Ria de Aveiro, a lagoon in northern region of Central Portugal, oyster fattening is performed through an extensive system where the feed is exclusively natural. Life cycle assessment (LCA) is a methodology that can be used to answer many questions that are traditionally not considered in seafood sustainability schemes. The aim of this study was to apply LCA to evaluate the environmental impacts of oysters (*Crassostrea gigas*) produced from two aquaculture farms in Ria de Aveiro, which present different mortality rates (67% and 15%) and different average oyster production (40 t/yr and 25 t/yr), and to identify hotspots and support different policy makers involved in the value chains of seafood production to opt for the most environmentally friendly option.
The functional unit is the production of 1 t of fresh oysters (with shell) ready for the consumer market. System boundaries include maternity, transport of juveniles, farm (fattening, harvesting and washing, packaging, solid waste landfill, and end-of-life (EoL) of shells that die during the grow-out stages), transport to depuration, and depuration. Depuration involves placing the oysters in tanks with water treated by ultraviolet to remove microorganisms accumulated in the oyster. Mass allocation (mass proportion of each bivalve produced during a specific year) was used at the depuration stage, because the depuration plant has different species, namely, carpet shell clam, cockle, razor shell, blue mussel, otter shelllutraria, murex brandaris and wedge shell. The carbon sequestration due to oyster shells growth was also estimated. The consumption of oysters and EoL were excluded from the system boundaries. The characterisation factors used in this study are those suggested for conducting a Product Environmental Footprint.
Results show that the depuration stage is the hotspot for most impact categories, mainly due to the electricity consumed during the depuration operations in Portugal. The impacts of the maternity stage, specifically at the fattening, resulted mainly from the several materials used in the infrastructure, such as oyster iron tables and steel hooks and tables, diesel, and harvesting and washing. In this sense, the establishment of policies that encourage alternative EoL management of infrastructures (e.g. reuse or recycling) could improve the sustainability of oyster production.
Acknowledgement:
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Estimating the material flow of used lithium-ion batteries in Japan

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

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Recently in Japan, fire accidents possibly caused by lithium-ion batteries (LIBs) have been increasing at waste treatment and recycling facilities, which has led to an increased burden on municipalities and small WEEE recyclers in Japan. In this study, we estimated the amount of used LIBs and their material flow in Japan in order to obtain basic information for discussing an appropriate used LIB collection system. This study focused on small LIBs used in WEEE, which are considered the main causes of current fire accidents at facilities, and does not cover LIBs for electric vehicles and energy storage systems.

We estimated the amount of used LIBs in Japan by multiplying the number of end-of-life products using rechargeable batteries in use, the ratio of products using LIBs for each product category, and the weight of LIBs per product. The number of end-of-life products using rechargeable batteries was estimated based on the number of in-use and sold products or the average lifespan of products. The ratio of products using LIBs for each product category and the weight of LIBs per product were calculated based on our sample surveys of collected WEEE at facilities of municipalities and small WEEE recyclers in Japan. We then calculated the collection rate of used LIBs using the data of used LIBs collected through the voluntary collection system for used small rechargeable batteries and the collection systems for small WEEE. In addition, we estimated the amount of used LIBs collected by municipalities with being mixed with noncombustible waste from the data of our sample survey at facilities of municipalities. Based on the results, we draw the static material flow of used LIBs in Japan.

The total amount of used LIBs in Japan was estimated at 6,229 tons per year. Note that this amount is the total of approximately 20 major items of electrical and electronic equipment and the estimate is expected to increase slightly after adding the estimates for products excluded to date. On the other hand, the amounts of collected LIBs through the collection systems for used LIBs and small WEEE were 730 tons (FY2020) and 120 tons (FY2018), respectively. The collection rate of used LIBs in Japan was calculated to be 14%. In addition, the amount of used LIBs collected by municipalities with being mixed with noncombustible waste was estimated to be 828 tons. The total amount of these collected LIBs was 1,678 tons, which corresponds to 27% of the estimated amount of used LIBs in this study. Other flows such as collection routes for cell phones and PCs, but those are small. The destinations of approximately 70% of the used LIB emissions in Japan are still unknown. Other possible flows include the combustible waste and packaging and container plastics collections by municipalities, the collection as hazardous industrial waste, and hibernating at households, etc. Further understanding of the flow of 70% of used LIBs is needed to discuss the responsibilities of each stakeholder in establishing an appropriate collection system for used LIBs.

Going beyond generic LCA: A framework for mass-deployment of customized semi-automated carbon footprinting

Monday, 3rd July - 10:15: Ex-ante LCA 1 (B0.25 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Marit Salome Rognan [1], *Guillaume Majeau-Bettez* [1], *Manuele Margni* [1]

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Advancements in life cycle assessment (LCA) and environmentally extended input-output analysis enable quick, generic estimations of the environmental footprint of almost any type of product and service. To go beyond a generic estimate to an assessment based on actual and specific supply chain data remains too costly and requires significant data sharing between supply chain actors and the LCA practitioner. This, coupled with companies' reluctance to share proprietary information to third parties on their purchases, sales, and emissions, makes it impracticable to assess products and services with specificity. Although the demand for LCA is growing in regulatory applications, such as mandatory corporate greenhouse gas reporting and product carbon footprint disclosures, nearly all upstream impacts are estimated using generic, proxy, and often outdated datasets. This significantly limits the potential of LCA to give reliable support to decision making when it comes to discriminating products based on their environmental footprints. Achieving specificity at a large scale in LCA requires fundamentally changing the way emission data is collected, stored, and exchanged.

The objective of this research project is therefore to define and develop a framework that facilitates the mass deployment of semi-automated, supply chain-specific cradle-to-gate carbon footprint calculations, without requiring the exchange of sensitive proprietary data. Key features of the framework include decentralizing the inventory collection and impact assessment, so that production functions remain with the respective companies. More specifically, they remain in an automated calculator that is linked to a database with carbon footprints reported by other actors, allowing them to instantly capture changes in suppliers' footprint disclosures. While this would substantially reduce the effort of an attributional carbon footprint assessment, the solutions and features proposed in the framework present new challenges, which are identified and discussed in this project in terms of how they can be addressed in practice and their implications.

This research project offers important insight into how we can get to a point where every product and service has its unique carbon footprint transparently displayed, the same way it has a unique monetary cost. Access to carbon footprints with more specificity would not only help consumers to reduce their consumption-based impacts, but it could also push companies to take accountability for, and reduce, their indirect impacts. The framework and overall findings, however, are applicable for any impact category, not just that of climate change.

Land-free Bioenergy from Circular Agroecology – A Diverse Option Space

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Fei Wu [1]***, Adrian Muller*** [2]***, Stefan Pfenninger*** [3]

1. ETH Zurich, 2. Fibl, 3. Technical University Delft

[Student submission]

Bioenergy receives massive subsidies and is envisioned to play an important role in providing negative emissions, predominantly using dedicated energy crops. However, dedicated biomass is controversial as it may compete with food production and biodiversity protection [1]. A less controversial alternative could be land-free ancillary biomass not primarily grown for energy and without land/food/feed competition, for instance, by-products and waste with low opportunity costs [2].

Nevertheless, the potential for ancillary biomass may considerably vary depending on what future agricultural practices are in place (e.g., organic farming and waste reduction). Using the food system model SOLm [3], we explore how changing agricultural practices would affect the future global potential of ancillary biomass for energy use. We find a diverse option space where a similar range of land-free biomass potential can be derived from very different mixes of agricultural practices, thus, with different environmental impacts on the food system. Moreover, we identify the potential nutrient deficit as the key constraint for sourcing ancillary biomass for energy use from agroecological production systems with low mineral fertilizer use. However, we can amend the nitrogen deficit by increasing the circularity of the food system, for instance, by shifting bioenergy conversion pathways to recycle more nutrients or through improving wastewater treatment to recycle human excretes. Our results provide modeling support for global policymakers by revealing the diversified and flexible option space between sustainable food and clean energy systems using land-free ancillary biomass.

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Analysis to identify key parameters for estimating generation of used PV panels

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ken MATSUOKA [1], ***Yusuke FUJII*** [1], ***Ryu Koide*** [2], ***Shinsuke Murakami*** [1]

1. The University of Tokyo, 2. Material Cycles Division, National Institute for Environmental Studies

The demand for decarbonization and resource security has raised the rapid introduction of PV panels around the world. In Japan, the Sixth Strategic Energy Plan (Cabinet Decision in October 2021) states that Japan will address maximum introduction of renewable energy as major power sources on the top priority. Prior to the large-scale facilities introduction, it is important to consider resource recycling after the facilities are decommissioned.

There are global estimates of the volume of end-of-life PV panels by the International Renewable Energy Agency (IRENA), etc., and in Japan, the timing and scale of future generations estimated in several previous studies. These estimates are mainly based on the consideration of failure. However, since there are not only physical causes but also other factors, such as facility upgrades to improve profitability, it is necessary to consider complexity when estimating generations of used PV panels.

We analyzed the uncertainties that arise when these multiple factors are considered simultaneously, demonstrated the need to estimate generation for each condition while taking into account the uncertainties, and identified the parameters that are important in estimating reliable generation volumes by applying Regional Sensitivity Analysis (RSA) method.

First, the long-term installed capacity for all over Japan was determined. Actual values up to 2020 were used, and after 2021, based on existing studies, it was assumed that the total installed capacity (about 400 GW) would be achieved, so that 50-60% of domestic electricity demand would be met by renewable energy sources by 2050, and in the case of competition between wind and solar power, the latter would prevail, and then maintained until 2100.

Next, the following estimation model for used PV panels was developed. Initially, the model was set up to include power producers who would make business feasibility decisions based on changes in market conditions and reductions in power generation. It was then assumed that individual power producers make the decision each year and decide whether to replace their panels or to continue to use them until the end of the warranty period, and that the panels are discharged as waste after replacement. In addition, for each facility, the failure rate of the panel after installation was given by the Weibull distribution and it was assumed that the equipment would be discharged uniformly after failure. Then, the installation is carried out in each year so that the installed capacity for each year set in a. is achieved. The module weight per unit capacity is assumed to decrease until 2050, and to then remain constant.

RSA was performed on the model to evaluate the importance and impact on uncertainty of parameters such as changes in market conditions, generation reductions, the Weibull distribution for failures, weight per unit capacity, etc., and to identify parameters that are important for reliable generation estimates.

By manipulating each parameter in parallel using RSA, generations were estimated for each condition reflecting various uncertainties. For example, if facility renewal is encouraged under certain conditions, there will be a significant introduction of new panels and emissions from existing ones that need to be considered, especially from a resource efficiency perspective. The results indicate the need to estimate generations for each condition, taking into account uncertainties, and confirm the important parameters, where we found RSA quite useful.

Regionalization of water scarcity characterization factors to Peruvian basins using the AWARE method

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Joan Sanchez-Matos [1], ***Ramzy Kahhat*** [1], ***Ian Vazquez-Rowe*** [1]

1. *Pontificia Universidad Católica del Perú*

Peru is composed of three Hydrographic Regions: Pacific, Atlantic (i.e., the Amazon basin), and Titicaca. These basins show different levels of water availability and demands, and consequently different levels of water scarcity. Water scarcity is currently a critical environmental concern and its effects are being enhanced by climate change. Considering that water scarcity is a local-dependent environmental impact, it is relevant to increase its representativeness to assess the environmental impact on water resources, especially in heterogeneous regions such as Peru. In this sense, this study aims to develop regionalized water scarcity characterization factors (CFs) for Peruvian watersheds using the Available Water Remaining (AWARE) method (Boulay et al. 2018) and apply these CFs to locally-produced agricultural products. The novelty of this study is linked it being the first attempt to regionalize environmental impact assessment methods at a national scale in Peru.

Updating current AWARE CFs to regionalized CFs was carried out with spatial resolution according to official watershed delimitation and using official data on water demand and availability from Peru. The AWARE CFs were updated as follows: a) the original spatial resolution from AWARE (0.5° x 0.5°) was redefined per hydrological units (HUs) delimited by the Peruvian National Water Authority (ANA, *Autoridad Nacional del Agua*); b) data on water availability were gathered from the PISCO_HyM_GR2M model (Llauca et al. 2021); and, c) human water demand was collected based on two approaches. On the one hand, domestic water demand was estimated using the average per capita water consumption of Peruvian citizens and the population density in each HU. On the other hand, agricultural, industrial, and livestock water demands were collected from water use rights (water use licenses) available in the Peruvian Water Observatory database (ANA 2016) rather than from WaterGAP (Alcamo et al. 2003). Ecosystem demand was based on the environmental water requirement method proposed by Pastor et al. (2014) and originally used in the AWARE method. Once computed, the updated water scarcity CFs were used to recalculate the water scarcity impact of agricultural products (i.e., asparagus, avocado, and grapes) reported by life cycle assessment (LCA) studies carried out along the Peruvian coast.

The results revealed high differences between updated and original water scarcity CFs, both on spatial and temporal terms, especially along the Peruvian hyper-arid coast, where the CFs showed the highest values. These differences are linked to the different data sources, and the absence of agricultural water demand considered by WaterGAP in many months in areas with high agricultural activity. When these updated CFs were used in order to recalculate the water scarcity impact of agricultural products, the results showed higher water scarcity impact than those obtained with original water scarcity CFs, an important outcome that must be taken into consideration in environmental certification schemes.

Overall, the updated CFs for Peruvian basins constitute an opportunity to improve the representativeness of the water scarcity impacts calculated for products produced in the Peruvian context. Furthermore, the results revealed high pressure over water resources in areas with low water availability, which warns about the need of increase the efforts to maximize initiatives of water management and formalization of water use.

A Top-Down approach for downscaling sectoral emission budgets. A case study of Canada's construction sector

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 10:00: Future resources (B0.31 KOG)

Hatzav Yoffe [1], ***Keagan Hudson Rankin*** [2], ***Christian Bachmann*** [3], ***I. Daniel Posen*** [1], ***Shoshanna Saxe*** [1]

1. *University of Toronto,* ***2.*** *University of toronto,* ***3.*** *University of Waterloo*

The world's growing population is demanding massive construction of buildings, infrastructure and services, which in turn, results in significant primary resource consumption (e.g. steel, concrete, wood) and associated greenhouse gas emissions (GHG). Global construction is already responsible for >12 Gigatons (20%) of annual GHG emissions[1], a number that is rapidly growing[2]. In line with the Paris agreement, Canada has committed to cutting GHG emissions in half (46%) by 2030[3], heavily constraining the allowable emissions for construction. This reduction is challenging considering the immense construction required in the coming years due to substantial infrastructure renewal needs and Canada's projected population growth. While material industries are exploring low GHG manufacturing pathways, large-scale decarbonization will take time, and materials manufacturing will remain a large emission source in the coming decades.

A key challenge in Canada, and other fast-growing countries, is building the necessary infrastructure that provides equality and dignity to a growing population while rapidly reducing the GHG emissions associated with the construction sector. While a qualitative understanding of 'we must build more while emitting less' is increasingly common, its tensions are under-investigated and practical guidance on how to proceed slimmer still. Quantitative understandings of the construction sector footprint within the total emission budgets are extremely limited[4], inhibiting our ability to update what and how we build or plan future construction. This is exacerbated by the absence of construction as a sector within the United Nation's Intergovernmental Panel on Climate Change (IPCC) national emission reports.

This presentation will explore: 1) estimating current GHG emissions in the construction sector; and 2) establishing future construction sector GHG emissions budgets considering potential tradeoffs with other sectors, using Canada as an example case study.

The study analyzed Canada's construction sector emissions using 'Open IO Canada'[5], an Environmentally-Extended Input-Output (EEIO) model, which evaluates the environmental impact of economic sectors based on high-resolution national statistics paired with pollution release datasets. This IO approach, which facilitates upstream and imported emissions, was applied after failed attempts to back-calculate the construction emissions from Canada's IPCC national report (which will also be briefly discussed). The second part of the study explores pathways to achieve Canada's emission reduction goals by a.) Preserving the construction sector's current share of emissions; and b.) allowing construction emissions to grow by advancing emission reductions in other sectors (e.g. transportation, energy).

Preliminary results suggest that construction emissions are 13% (90MTCO2e) of Canada's total emissions. Specifically, we found *Residential Construction* to be, by far, the largest contributor of GHG emissions nationwide (39%), more than *Transit Infrastructure* (12%), *Office and Commercial Buildings* (6%), and *Industrial Buildings* (3%). Furthermore, in Canada's densely populated and most emission-contributing provinces (Quebec, Ontario, British Columbia), residential buildings make up at least half of the construction emissions.

The study demonstrates the use of EEIO to calculate the construction sector's footprint, including both subsectoral and spatial emissions disaggregation. The study further explores real limitations in terms of GHG budgeting for future construction, as well as emphasizing the importance of downscaling emission budgets to a regional and city level and translating it into carbon-aware planning and development strategies.

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Market and Grid Required for Renewables-Dominated Electricity Systems

Monday, 3rd July - 12:28: Energy (short presentations) (B0.16 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Gjalt Huppes [1], *Ruben Huele* [1]

1. Leiden University, CML

Renewables and Batteries

Wind and solar electricity are both non-dispatchable and intermittent. They will expand dramatically in primary production of electricity. Final use of electricity is also intermittent, and not aligned with intermittent supply. Reserve capacity can equalize electricity production and use, as with pumped hydro, flywheels, condensers, and: batteries. Decentral batteries will develop a combined capacity able to overcome the difference between primary production and final use over days to weeks, see (Xu, Behrens et al. 2023). Discarded car batteries add to this *secondary production capacity* in the longer term, with later recycling. Batteries can react to price changes in milliseconds, helping stabilize the grid automatically. But will this all happen in the current electricity market and the current grid, in Europe tending towards renationalization? Certainly not!

Market and Grid

Markets have developed for wholesale high-voltage production, at time scales of days, hours, and shorter. Wholesale producers are thus linked to high-volage Transmission System Operators (TSOs) responsible for voltage and frequency stability. For demand variation, also at lower voltage levels, some market mechanisms have developed, least so in the low-voltage decentral domain. Using car batteries for secondary production will only come if the selling price is higher than the buying price for charging the battery. Car batteries function for the car anyway, so they come nearly for free.

In the grid-to-come, with distributed production at all voltage levels, bidirectional flows must be accommodated. Long-distance transport lines are needed from areas with cheap solar and wind to high-use areas.

Design principles

-The grid system consists of independent nodes, with multiple line connections between them.
-The grid system is near continental.
-Producers are connected to at least one node, preferably more.
-Nodes can contain transformers, to link between different voltage lines.
-Internal grid lines and inter-grid lines can create flexibility, also for supporting grid stability.
-New millisecond electronics allow for real-time grid stabilization.
-Prices are variable at milliseconds level, for all market participants.
-Electricity from a node must have an equal price for all purchasers, at any moment of time.
-Grid transport costs in each node must be covered as part of the price of electricity sold.
-Congesting damage in a grid node must be prevented at any time.
-Congestion pricing, steeply rising, is the prime means to prevent congestion damage.
-Proceeds of congestion pricing go into a public fund for grid improvement.
-Private monopolies in the grid system must be prevented, as are public monopolies where possible.
-Each node operator can acquire electricity from several linked nodes and from external producers.
-Each node operator sells electricity to other grid nodes, and to users.
-There are no fixed connection costs, similar to other markets that do not charge for the right to shop.
-Price and quantity information for all flows is real-time available for grid node operators and clients.
-He who owns a market shall not trade in that market.

Results

Variable priced primary and secondary markets can solve the intermittency problem of renewables automatically.
Avoiding monopoly in node markets induces lowest production cost. Any final user receives electricity for the lowest possible cost, also dynamically.
The collectivity of Transmission System Operators is responsible for grid design and development at all voltage levels.
Car batteries can earn back many thousands of Euros over their lifetime.

Light-Duty Passenger Vehicle Electrification in China and Associated Greenhouse Gas Emissions from 2021 to 2050: A Dynamic Fleet Perspective

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Bin Shui [1]

1. City University of Hong Kong

The increasing road transportation continued to be the most vital contributor to greenhouse gas (GHG) emissions from fossil fuel combustion, mainly due to light-duty passenger vehicles (LDPVs). As the developing country with the largest LDPV fleet, China is facing tremendous pressure to find a sustainable way in the road transportation sector. The electric vehicle is seen as a promising technology to realize mitigation targets in road transportation. However, the traditionally vehicle-bases assessment lacks the ability to capture the dynamic impact of fleet turnover and neglects the temporal distribution of emissions. The long-term and fleet-scale impacts of the electric vehicle promotion in China are still underexplored.

To investigate the mitigation potential and future energy demand of LDPVs electrification, a dynamic fleet-based life cycle assessment framework is constructed for China under the Shared Socioeconomic Pathways (SSPs). Three socioeconomic pathways (SSP1, SSP2, and SSP5) and three electrification speed (BAU, EV2050, and EV2040) are assumed to represent the future development of LDPV fleet in China. The annual GHG emissions of LDPV fleet from 2021 to 2050 under the nine scenarios (SSP1-BAU, SSP1-EV2050, SSP1-EV2040, SSP2-BAU, SSP2-EV2050, SSP2-EV2040, SSP5-BAU, SSP5-EV2050, and SSP5-EV2040) are calculated. The fine-grained bottom-up assessment model considering the regional disparity and three main phases (i.e., production, operation, and end-of-life) is established to shed light on the future road transportation decarbonization policy making.

Three main finds have been revealed. Firstly, electrification is not a silver bullet. The annual fleet GHG emissions will peak at 1.17~1.28 Gt CO_2 eq between 2029 and 2034, which will be late than the planned national carbon peak year (2030). Although the annual emissions will gradually decrease to 0.54~0.93 Gt CO_2 eq in 2050, the electricity system and material supply chain will face great pressure to realize the mitigation target. The electricity demand for vehicle charging will reach 630.4~828.8 TWh under the aggressive electrification scenario (EV2040), equivalent to 53%~69% of the 2020 annual national residential electricity consumption. A sustainable pathway with lower grid carbon intensity and restricted fleet scale is the cornerstone to reduce emissions. Secondly, the electrification strategy shows significant underlying emissions reduction, and the mitigation potential increases significantly with the electrification speed accelerates. Compare to the SSP2 pathway with the business-as-usual electrification speed, seven scenarios show an underlying reduction in the cumulative emissions from 2021 to 2050. The mitigation potential ranges from 1.2 ~ 7.5 Gt CO_2 eq. Under the sustainable pathway (SSP1), the aggressive electrification strategy (SSP1-EV 2040) reduces accumulative life cycle GHG emissions by 7.5Gt CO_2 eq (21%) compared to the business-as-usual scenario (SSP2-BAU). Thirdly, the regional distribution of GHG emissions shows a downward trend from east to west, demonstrating the essence of China's regional-specified strategy. The GHG emissions from the use phase in each province reveal that the grid emission factors have a progressively greater impact on total emissions as the electrification trend accelerates.

In summary, decarbonization in the road fleet would remain an empty slogan without transfers of clean and reliable grid power, embracing a sustainable lifestyle, and elimination of key material shortage. The material supply chain and electricity system should be coordinated under a more sustainable pathway to realize the mitigation target.

Material flow analysis of end-of-life electric vehicle batteries using agent-based modeling

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Miriam Stevens [1], ***Shweta Singh*** [1], ***Sarang Supekar*** [2]

1. Purdue University, 2. Argonne National Laboratory

Uncertainty over the desired and actual end-of-life (EOL) pathways for electric vehicles (EVs) has implications for the development of recycling infrastructure and logistics coordination. If EV batteries are diverted to stationary energy storage or other second use applications, there will be a delay in when their embodied materials become available for recycling. This potential delay makes forecasting the supply of materials for recycling challenging and reliable supply forecasts are needed for the optimal design of recycling infrastructure. Recycling facility size, expected yield, and costs – and other factors affecting long-term market viability, for recycling and other second use applications – depend on reliable knowledge of the quantity and composition of supply. Plausible projections on how the reuse of EOL EV batteries in secondary applications may affect the supply of batteries available for recycling and by extension the supply of secondary materials that can be used to offset primary critical material demand would aid in planning regional closed loop supply chains for battery critical materials. To that end, we use an agent-based model (ABM) that incorporates the decisions made in determining the end-of-life fate of EV batteries to provide insight into how the supply of EV batteries may be diverted to available second use pathways including remanufacturing, repurposing, and recycling. The ABM framework developed by the US National Renewable Energy Laboratory (NREL) for circular economy strategies for solar PV, wind energy systems, and hard disc drives has been adapted to capture the dynamics of an EV battery collection system in which cost, battery state of health, and the subjective likelihood of firms to reuse batteries are factored into a battery's selected EOL pathway. To bolster EV battery recovery, starting with the first generation of EV batteries, this work is focused on the dynamics affecting the collection of nickel-metal hydride (NiMH) hybrid electric vehicle batteries. However, the types of decisions made and assumptions in this work regarding the collection, reuse, and recycling of NiMH batteries could also be applied to lithium-ion batteries (LIBs).

Challenges in aquaponic food production – considering the social paradigm of sustainability

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Marissa Breitenstein [1], ***Elisabeth Bautista*** [1], ***Andrea Hicks*** [1]

1. *University of Wisconsin-Madison*

Aquaponics as a food production system is being investigated as more sustainable method than traditional techniques, such as aquaculture. Aquaponics is a closed loop food production method, propagating both fish and plants. Because aquaponics is a relatively new technology, learning the potential challenges and reasons behind the demise of related companies is imperative for the success of current and future operations. Possible failure modes include volatility in product distribution, disease spread in the system, and limitations in operators knowledge or experience. To study these phenomena, a survey will be distributed to cold weather aquaponics and aquaculture operations in cold climates. Surveying operators on challenges specific to their business and gaining data on prior knowledge and experience enables a clear distinction to be drawn about the failure modes and the potential for mitigation of failure in the future. An additional consideration to helping the success of future aquaponics operations is investigating the potential for value-added and value-recovered processes to be added to an aquaponics operation. A value-added process is the addition of a process to further add financial value to the final product being sold. A value-recovered process is using byproducts of a system to create other valuable products from the system that would have otherwise been waste. The survey covers the operator's willingness to invest in the potential additions, while also understanding the possible benefits of making those changes to their particular operation. Collecting data on interest and willingness to pay for value-added/recovered process additions to their particular operations facilitates optimized decisions for aquaponics operators to fully benefit financially for utilizing a more sustainable food production method.

Sustainable Mobility in Times of Crises

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Mira Kopp [1], ***Carmen Pérez del Pulgar Frowein*** [2]

1. Friedrich Schiller University Jena, 2. Helmholtz Centre for Environmental Research

The management of recent crises has changed urban mobility patterns in unprecedented ways. The effects of the COVID-19 pandemic on mobility patterns became particularly visible in cities, where overall movements decreased, public transport companies suffered from low customer numbers and empty streets turned into pop-up bike lanes. Accordingly, a decrease in local air pollution has been widely reported for many cities at the start of the pandemic. However, little is known about the long-term and full supply chain environmental effects of these new urban mobility patterns. Using Berlin as an example, we analyse how movement levels and the modal split of that movement influenced emissions and their upstream effects throughout the pandemic. The analysis combines traffic counts, tracking, and survey data with environmental factors derived from Life Cycle Inventories. Our results show that there was an overall reduction of mobility-related emissions, but this was due to the decrease in movement in general instead of more sustainable modal choices. As overall movement levels declined, not all modes were avoided equally, and a less sustainable modal split was adopted. Moreover, potential reductions in emissions further up the supply chain were not realised due to the slowly responding demand for vehicles and public transport planning. To prevent a rebound in emissions while movement levels return, it will be crucial to accustom car drivers to collective means of transport again. Further, the continued promotion of active mobility will be necessary to keep freshly produced bicycles in use and to leverage the increased accessibility of road space for cyclists.

Effect factors for ecotoxicity from plastic additives in the aquatic ecosystem

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Naiara Casagrande [1]***, Carla Silva*** [1]***, Francesca Verones*** [2]***, Paula Sobral*** [1]***, Graça Martinho*** [1]

1. *MARE - Marine and Environmental Sciences Centre | ARNET - Aquatic Research Network Associate Laboratory, NOVA School of Science and Technology, NOVA University Lisbon,* ***2.*** *NTNU*

In the last decades, a considerable amount of plastic from anthropogenic activities has reached the aquatic ecosystem. Once in the environment, plastics exposed to physical, chemical and biological processes degrade and fragment into smaller and smaller particles. In addition to this fragmentation process, there is a release of various chemical substances from the plastics. These substances are additives added to the plastic products during the manufacturing process with different functions, such as plasticizers, heat and light stabilizers, pesticides or flame-retardants. Aquatic species, which are exposed to these substances can be damaged due to the potentially toxic effects of these substances. However, life cycle impact assessment does so far a poor job of assessing the environmental consequences of these additives. Characterization factors for plastic additives are, to our knowledge, not available and effect factors exist for only 6 additives/groups of additives as well as a Generic factor. We present the calculation of additional and improved effect factors of plastic additives on aquatic ecosystems that can be integrated into the impact category of ecotoxicity. Our database has 415 data points for the effects of plastic additives on 73 aquatic species belonging to nine different phylum. Additives included heat and UV stabilisers, plasticisers, flame retardants, pesticides and photoinitiators. We collected information for both lethal and sublethal endpoints in freshwater and marine species for at least three trophic levels (e.g. decomposers, primary producers, primary as well as secondary consumers) and each substance, aiming to have factors representative of the ecosystem as recommended by USEtox. Different gathered data points such as LC50, acute EC50, chronic LOEC and acute and chronic NOEC were harmonized into chronic EC50 by applying extrapolation factors. We used the following equation for the effect factor derivation: *Effect Factor (EF) =* $0.5/HC50_{EC50}$, where $HC50_{EC50}$ is the geometric mean of chronic EC_{50s}, which is the concentration at which 50% of the test organisms are affected. In total, we calculated 22 effect factors. The unit of the effect factors is the Potentially Affected Fraction (PAF) of species over time and the mass of the chemical released. This includes four effect factors for substances grouped into the same chemical classification (Alkylphenols, Benzophenones, Brominated flame retardants, and Phosphates), 16 effect factors for single substances as well as one effect factor for other chemicals. In addition, we calculated the generic effect factor including all the data points. Overall, the results ranged between 20.54 $PAF \cdot m^3 \cdot kg^{-1}$ for DEP (diethyl phthalate) and 6529.98 $PAF \cdot m^3 \cdot kg^{-1}$ for Triclosan. There is also a variation in the results of effect factors comparing single substances from the same group. For example, in the group of Alkyphenols, while the effect factor for 4-Nonylphenol is 5885.22 $PAF.m^3.kg^{-1}$, it is 298.83 $PAF.m^3.kg^{-1}$ for Nonylphenol. These effect factors will need to be combined with fate and exposure factors for the substances to derive a characterization factor for toxicity caused by additives in aquatic species. New indicators on this issue allow an improvement in the analysis of the plastic life cycle and provide information to support decision makers.

Transport dependence on oil: Could transport electrification offset near-future strains on net energy flows from liquid fossil fuels?

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Antonin Berthe [1], ***Pierre-Yves Longaretti*** [1], ***Olivier Vidal*** [2], ***Emmanuel Prados*** [1]

1. Inria, 2. Institut des Sciences de la Terre

Recent articles, reports and announcements support the evidence of net energy peak oil being to be passed or having been passed, and this may occur more from the supply side than from the demand one. This raises concerns about transport as it relies on oil for 95% of its supply, thus raising concerns on global economies as transport is central for a globalised trade.

In this work, we then focus on the transport impact of net energy oil supply flows reduction. We use a quantitative energy and biophysical approach for this purpose. Our main point of discussion is related to time-scale constraints, focusing more specifically on possible tensions between the time-scale of oil net energy decrease versus the time-scale of oil net energy use reduction or substitution.

First, we study the possibilities of short-run oil substitution by other fossil products. Next, we look at possible oil savings through transport electrification.

Some barriers can be expected to a 20-30 years massive vehicle electrification.

We focus more specifically on the passenger battery electric vehicle economic accessibility. Battery electric vehicles are currently 40% more expensive than traditional internal combustion engine vehicles. Because of cost difference and moderate benefits, not all household can afford the switch to electric vehicles. Moreover, as electric vehicles only represent a 1% share in the total worldwide number of vehicles and are emerging, the second-hand market is nearly unexisting.

We then design a model of passenger electric car purchases and sales between income categories in order to characterize the rate of replacement of combustion engine vehicles. We represent different income categories characterised by their number, their investment capacity in new vehicles, taking into account the mean vehicle lifetime and price evolution.

This study is a first step towards a refined modelling involving coupling with a biophysical IAM dedicated to a comprehensive modelling of energy-material mutual dependencies in an energy transition (the MATER model). The talk will present the first results of this ongoing research effort.

Development of a spatially explicit model to evaluate widespread impacts of reduced ocean pH and calcite saturation levels

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Sedona Anderson [1], ***Francesca Verones*** [1], ***L. Scherer*** [2]
1. NTNU, 2. Leiden University, CML

Ocean acidification is predicted to triple by the end of the century. This could cause unprecedented effects on biodiversity, on top of the other widespread pressures causing an ongoing sixth mass extinction. The world's oceans absorb approximately 30% of anthropogenic carbon emissions. Through this absorption, CO2 is dissolved in oceanic water, resulting in chemical reactions that ultimately cause pH reduction and a reduced saturation state of calcium carbonate. These two effects of oceanic CO2 absorption have widespread negative effects on marine species.

Since pre-industrial times, ocean pH has declined by an average of ~0.11 units and is predicted to decline by another 0.3-0.4 units by the end of the century. This is the highest level of ocean acidity in recorded history outside of the Paleocene-Eocene Thermal Maximum. One effect of ocean acidification is the lowering of calcium carbonate saturation states, which significantly impacts shell-forming marine organisms. Though this is perhaps the most well-studied impact of ocean acidification, on a broader scale the many effects of acidification on both calcifying and non-calcifying organisms are not well-understood. This is also true within LCA; some models exist but need to be expanded upon to accurately understand the impacts of ocean acidification.

Site-generic midpoint indicators for assessing impacts from carbon monoxide, carbon dioxide, and methane exist. In addition, species sensitivity distributions (SSDs) for ocean acidification exist but distinguish at most three climate zones and are often limited to calcifying organisms . However, oceanic pH varies significantly around the globe (between 7.9 and 8.3), and different ecosystems have varied reactions to changes in water chemistry due to different species being present. Additionally, there are widespread negative impacts on non-calcifying organisms as well (which include acidosis, reduced survival of fish larvae, and changes in organism behavior, among others).

Our research builds on previous models to create a spatially explicit endpoint model for ocean acidification that includes both calcifying and non-calcifying organisms. We will present a spatially explicit fate model for the changes in saturation of seawater with carbonate materials, aiming at a coverage of 232 marine ecoregions. In the future, this will be combined with new SSD curves, aiming to include 12 marine realms and including non-calcifying organisms. Ultimately, these will be used to derive effect factors. The combination of the updated fate and effect factors will result in spatially explicit characterization factors for impacts from ocean acidification. These characterization factors will be used in the Horizon Europe project BAMBOO to identify leverage points in order to halt and reverse biodiversity loss caused by global trade networks.

Decarbonizing future cement production: A prospective Life Cycle Assessment using global Scenarios from an Integrated Assessment Model

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Amelie Mueller [1], *Carina Harpprecht* [2], *Romain Sacchi* [3], *Ben Maes* [4], *Mariësse Van Sluisveld* [5], *Vassilis Daioglou* [5], *Branko Šavija* [6], *Bernhard Steubing* [7]

1. Leiden University, Institute of Environmental Sciences (CML), 2. German Aerospace Center (DLR), Institute for Networked Energy Systems, 3. Paul Scherrer Institute, 4. University of Antwerp, 5. PBL Netherlands Environmental Assessment Agency, 6. Technical University Delft, 7. CML Leiden

With an annual production volume of 4.3 Gt, cement is an important construction material, indispensable for the provision of various socio-economic services. Cement is a major driver for climate change, emitting 8% of the global energy-related greenhouse gases (GHG). Moreover, direct GHG emissions from cement production have increased by 1.5% per year between 2015 and 2021, jeopardizing the sector's efforts to reach the emission reduction targets of the Paris agreement. Thus, long-term transition pathways towards a global low-carbon cement industry are needed. Ideally, these pathways are developed using a systemic approach, e.g. in coherence with macro-economic developments, such as decarbonization of other sectors, and considering biophysical limits, such as availability of resources. Moreover, they need to overcome the carbon-tunnel vision of existing studies by also considering burden shifting to other environmental impacts.

The goal of this study is to assess potential environmental impacts of possible transition pathways to low-carbon cement production for different climate targets using prospective LCA (pLCA). We use global cement production scenarios from the Integrated Assessment Model (IAM) IMAGE to improve the macro-economic coherence of the transition pathways. We assess 3 scenarios: a business as usual (SSP2-Base), 2°C-compliant (SSP2-2.6) and 1.5°C-compliant (SSP2-1.9) scenario. They cover 26 world regions and the years 2020 to 2060. The IAM scenarios are integrated into the life cycle inventory database ecoinvent v3.8 using the python package *premise*. They are complemented with IMAGE-based background scenarios for electricity, fuels, transport and steel, to include supply chain decarbonization effects. This prospective LCA study is cradle-to-gate and, for consistency, only includes technological changes foreseen by the IAM. As such, technologies at low technological readiness level or demand-side mitigation options are not considered.

Our results show that by 2060 the climate change impact of the cement sector is substantially reduced in the more climate-ambitious scenarios compared to the business as usual scenario. This reduction is mostly caused by a large-scale roll-out of CCS and a higher share of bio-fuels, while efficiency improvements only contribute to a lower extent. We found that decarbonizing electricity generation in the background can considerably reduce CO_2 emissions for cement production. Despite substantial reductions in CO_2 emissions, net-zero cement production is not reached globally by 2060. The residual emissions between 2020 and 2060 claim a significant part of the remaining global carbon budgets of the scenarios. Furthermore, we found that the reductions in climate change impacts coincide with a burden shift towards other impact categories, such as land use and material resources, and a higher future energy demand.

Rapid and drastic measures are required to close the gap between the currently slow deployment rate of CCS in the cement industry and the high CCS adoption rates required in the climate-ambitious scenarios over the next decade. Policy makers must also ensure that the high demand for biofuels and low-carbon electricity required for economy-wide decarbonization can be met. Future research could explore if expanding this production-focused model to include mitigation levers along the entire cement value chain could lead to feasible pathways to net-negative cement production.

The strategies to improve the circularity of Taiwan's food system: Findings from nitrogen and phosphorus flows

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Yi-Hsiang Lee [1], ***Pei-Te Chiueh*** [2]

***1.** Graduate Institute of Environmental Engineering, National Taiwan University,* ***2.** National Taiwan University*

While nitrogen (N) and phosphorus (P) are both necessary for plant and animal growth, they also have the potential to contribute to eutrophication, acidification, and global warming. As a result, unsustainable food production and consumption practices currently pose serious risks of environmental degradation to Taiwan. Nutrient cycling has thus been a crucial alternative for the overall sustainability of Taiwan's food system. Whilst previous studies have taken Taiwan as a case study and mapped relevant nutrient flows to illustrate resource efficiency, they have frequently been limited to only a few food products or supply chain stages.

Accordingly, this research is conducted to identify areas where to improve nutrient recycling rate and use efficiency in Taiwan through material flow analysis (MFA), focusing on element N and P flows and stocks in the agriculture and food production system. In this work, 8 main food groups across 5 supply chain stages (i.e., cropland, livestock, food processing, consumption, and waste management) are studied for the years 2016-2020. We combine national statistics datasets with parameters derived from literature to measure all primary inputs, outputs, losses, and recycling nutrient flows for each step of the food life cycle.

The MFA results show that the total N and P inputs of Taiwan's food system are 358.6 kt N/yr and 118.3 kt P/yr, which were largely through the importation of animal feed (169 kt N/yr and 87 kt P/yr) and synthetic fertilizers (105 kt N/yr and 23 kt P/yr). Around 86% and 48% of the annual supply of N and P are lost to the environment. The largest losses are those through municipal wastewater, manure management, and cropland erosion. To transition to a more circular nutrient system, Taiwan has to speed up the adoption of wastewater nutrient recovery technology, improve the way conventional animal manure is managed, and facilitate higher fertilizer use efficiency. Lastly, consumers' dietary change toward fewer animal-based products could significantly increase the system's overall efficiency in utilizing nutrients.

This study demonstrates how a comprehensive understanding of the movements of nutrient resources can enhance the strategic planning of the "circular agriculture" transition.

Digesting fossil infrastructure: producing hydrogen with repurposed materials

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hauke Schlesier [1]***, Harald Desing*** [1]

1. *Empa - Swiss Federal Laboratories for Materials Science and Technology, Technology and Society Laboratory*

The increasing urgency to prevent dangerous climate change above 1.5°C heating necessitates fast transitions in all sectors. The material demand of these transitions (e.g. to build wind turbines, electric vehicles and electrolysers) is expected to be several times the current annual supply for many technology metals and a significant share of bulk metal supply. Additionally, large scale decommissioning of fossil-fed power plants and coal, gas and oil extraction sites is required to mitigate emissions. One approach of mobilising materials or infrastructure for these transitions is to repurpose obsolete fossil infrastructure. Here, we estimate the material stock of obsolete fossil infrastructure that can be repurposed.

We want to exemplify repurposing with hydrogen. Even though hydrogen is debated as energy storage, it is also an essential building block for base chemicals. When hydrogen is produced via electrolysis and renewable energy (green hydrogen), it still has a substantial carbon footprint due to embodied emissions in materials (e.g. steel in wind turbines). We use European data on fossil stocks in a case study of green hydrogen production to investigate the environmental effect of reusing materials from fossil infrastructure to build photovoltaic and wind energy systems, as well as electrolysers. Emission reductions are mainly expected from avoided primary production of steel and copper. Also, using repurposed steel decreases exergy investments for wind turbine construction. Reusing materials from fossil infrastructure can thus speed up the energy transition and reduce life cycle emissions of green hydrogen-consuming processes and products.

Strategic scenario analysis of EU CBAM

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Bertram F. de Boer [1]***, Ranran Wang*** [1]***, Arnold Tukker*** [2]

1. *Institute of Environmental Sciences (CML) - Universiteit Leiden,* ***2.*** *Leiden University, CML*

The European Union (EU) is a leading player in the global initiative to combat climate change. The European Green Deal presents a comprehensive strategy to attain the EU's objective of reducing carbon emissions by 55% relative to 1990 levels by 2030 and to attain climate neutrality by 2050. The Carbon Border Adjustment Mechanism (CBAM) is a key component of the strategy, which reinforces the EU's reputation as a leading global advocate for climate action is a crucial climate measure that seeks to mitigate the risk of carbon leakage and support the EU's increased ambition in reducing greenhouse gas emissions (GHG) globally.

Phase 1 of CBAM is a vital step towards achieving global GHG reduction by pricing EU imports with emission intensities higher than the EU27 average, e.g., through the transfer of best-in-class technologies. However, the scope of phase 1 is limited to the direct impacts of conventional energy-intensive production and products, namely aluminium, cement, electricity, fertilizer, and iron and steel. Subsequent phases could consider a broader set of products and upstream GHG impacts.

We carry out a strategic scenario analysis of CBAM, revealing the low and high estimates of GHG reduction potentials of various CBAM policy designs. As such, we formulate a set of scenarios to account for varying levels of policy ambition concerning EU27 imports and global production and technology reshuffle and catching up. The scenario analysis results also distinguish direct and indirect impacts on producers and consumers. Our analysis is based on the EXIOBASE 3.8.2 product-by-product environmentally extended multi-regional input-output tables in 2019.

Our findings hope to better inform the development of subsequent phases of the EU CBAM by systematically laying out a range of possible consequences of strategic decisions.

Life cycle assessment of electric vehicle battery repurpose use cases

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Benedikte Wralsen [1]

1. University of Agder

Motivation: The electrification of vehicles is a strategic plan to contribute to climate and environmental mitigation. All these vehicles require a considerable battery pack each that replaces the traditional combustion engine. In a life cycle management perspective, the end-of-life stage also has to be planned for the electrification strategy to be environmentally sustainable (European Commission, 2020; Jiao and Evans, 2016; Olsson et al., 2018; Wrålsen et al., 2021). There are several reasons to examine and find smart solutions for post-consumer electric vehicle batteries: 1) The materials are potentially harmful for the environment if not managed sustainably (Pehlken et al., 2017); 2) several battery materials are on the European Union's critical raw materials list and will require increasingly more resources to extract raw materials (IEA, 2022); 3) the materials (e.g., cobalt, nickel, lithium) are economically valuable and prices of these have increased recently (IEA, 2022); 4) when there is remaining capacity left after use in the vehicle, there is both potential for economic gain and environmental benefit if the battery is repurposed (Ahmadi et al., 2017; Bobba et al., 2018; Rallo et al., 2020; Wrålsen and Faessler, 2022). Despite the intuitive assumption that circular economy efforts such as repurposing and recycling lead to environmental benefits, this has no guarantee (Zink and Geyer, 2017). Therefore, life cycle assessment (LCA) is recognized as an appropriate methodology to examine potential gains (Haupt and Hellweg, 2019; Peña et al., 2021).
Purpose: The purpose of this study is to assess repurpose of used electric vehicle batteries in terms of environmental sustainability. Different use cases for repurpose of these batteries in stationary energy storage systems are examined using LCA methodology. The findings will provide recommendations and decision-support for companies and energy policymakers regarding environmental footprints of different applications for used batteries.
Methods: Four different use cases for remanufactured batteries are assessed by applying primary data from Norwegian companies for the development of a new life cycle inventory. The data collected and applied include the processes related to preparing a used EVB for a second life in a different application. The use cases are detected in an ongoing research project. Industry partners in the project will provide relevant data. With this new data, the authors compare the potential environmental benefits of repurposing EVBs by performing a complete consequential LCA. Considering the consequential modelling approach, potential for avoided primary production has to be identified, building on earlier work (Rigamonti et al., 2020; Wrålsen and O'Born, n.d.; Zink et al., 2016).
Results and discussion: This study will show how LCA methodology can detect the potential environmental benefits and trade-offs of different environmental impact categories for battery repurpose use cases. Furthermore, the importance of the substitution coefficient on overall results will be illustrated through scenarios.
Life cycle inventory data for repurpose of batteries will provide insights into the processes required to extend the battery life. The impact assessment results will compare environmental footprints for two use cases "in-front-of-the-meter" (i.e., a battery system connected to the electricity grid on the utility side) and two "behind-the-meter" (i.e., connected on the customer side). Furthermore, the challenge of identifying the substitution coefficient for LCA of circular economy efforts will be discussed and the best possible solution will be applied. Hence, the findings suggest environmental viability of electric vehicle battery repurpose assessed through different scenarios.

Economic and environmental feasibility of hydrogen production from gasifying mixed plastic waste with carbon capture and storage

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***Kai Lan* [1], *Yuan Yao* [1]**

1. Center for Industrial Ecology, Yale School of the Environment, Yale University

The demand and consumption of plastics have been rapidly increasing over recent decades, and generating a huge amount of plastic waste due to the low plastic recycling rate.[1] From 1950 to 2015, only 9% of the cumulative plastic waste generation, 6,300 million metric tons, was recycled; more than 60% of the plastic waste was discarded.[1] Traditional mechanical recycling of plastic waste has challenges in incompatibility when recycling mixed plastic waste (MPW), thermal-mechanical degradation, and contaminations.[2] Compared to mechanical recycling, thermochemical recycling methods have shown advantages in processing MPW. Thermochemical recycling processes can produce a large variety of products among which hydrogen is one with a mature market and increasing demand. Given that most hydrogen is produced from fossil fuel globally, converting MPW to hydrogen has the potential to address worldwide challenges of rapidly growing plastic waste and reduce fossil fuel demand. For the large-scale development of plastic recycling technologies, it is critical and necessary to understand the economic feasibility and environmental performance of plastic waste to the hydrogen pathway. Several previous studies have used techno-economic analysis (TEA) to evaluate the economic feasibility, or life cycle assessment (LCA) to assess the environmental benefits of plastic wastes to energy products. However, few studies have explored the economic and environmental feasibility of MPW to hydrogen at a large scale with carbon capture and storage (CCS), or investigated the drivers of the economic and environmental performance of MPW compared to single-stream recycled plastic.

To address this gap, this study conducted an LCA and TEA coupled with the process-based model developed in Aspen Plus to assess the economic and environmental performance of hydrogen from MPW and recycled single-stream plastic in the U.S. and identify the opportunities for cost reduction. Our results show that the minimum hydrogen selling price (MHSP) of a 2,000 oven dry metric ton/day MPW plant with CCS ranges from US\$2.26–\$2.94 kg^{-1} H_2, which can compete with current fossil fuel hydrogen with CCS (US\$1.21–\$2.62 kg^{-1} H_2). To identify the opportunities for cost reduction, this study uses an improvement analysis to display the roadmap for reducing the average MHSP from US\$2.60 to US\$1.46 kg^{-1} H_2. If carbon credits are close to the CCS costs along with the low feedstock cost of MPW, the MHSP can be further decreased to US\$1.06 kg^{-1} H_2. The results show that hydrogen derived from MPW has lower life-cycle environmental impacts and MHSP than single-stream plastics. From an operational perspective, the steam/feed ratio directly affects MHSP, and the optimal steam/feedstock ratio varies by feedstock and generally increases as the feedstock cost grows. This study aims at providing a fundamental understanding of the economic and environmental performance of MPW to the hydrogen pathway. The presented results will inform the waste management industry with economically and environmentally preferable system designs and shed light on opportunities to reduce cost and environmental burden.

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How Much Plastic Norway Loses to the Environment?

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ahmed Marhoon [1], ***Francesca Verones*** [2], ***Daniel B. Müller*** [1]

1. *Norwegian University of Science and Technology,* ***2.*** *NTNU*

Plastic has become an essential material for humanity. Due to its versatility and affordability it has found its way into a wide range of applications and products. Despite the great benefits it has brought us, plastic products are often being mismanaged, and since plastic is very persistent in the environment, the continuous release of it since the ~1950s has resulted in it becoming omnipresent. This constant release has not only contributed to the accumulation of a novel material in the environmental compartments, but research has also shown that plastic is responsible for a tremendous impact on the biosphere, including pollution with toxic substances and entanglement.

These environmental impacts call for a better understanding of the plastic cycle, in order to identify the most relevant leaks and emission sources for the different types of plastic. Material Flow Analysis (MFA) is a well-established method for systematically mapping the stocks and flows of materials within a system including their environmental emissions, which makes it an effective decision-making tool for environmental assessment and system improvement.

In this study, we present an expansion of an already developed DPMFA model for the Norwegian plastic economy by adding five additional plastic polymers (PUR; PA; PC; ABS; and rubber) and several relevant product categories (e.g., tires and flushed products). We highlight the initial micro- and macro-plastics emissions to the biosphere and we distinguish their receiving environmental compartment (terrestrial, freshwater, soil or marine). Our model gives an initial detailed insight into the plastic flows to the environment in Norway and serves as an input for future studies aiming at quantifying the environmental impacts associated with plastic losses and for designing scenarios for changes within the Norwegian plastic economy.

Study of Vehicle-to-Grid introduction to reduce curtailment of renewable energy in a remote Island in Japan : Case Study of Tanegashima island

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Kazuki IGARASHI [1], *Hideaki KURISHIMA* [1], *Yasunori Kikuchi* [2]

1. Shibaura Institute of Technology, 2. The University of Tokyo

The introduction of renewable energy is essential to realize a carbon-neutral society. However, remote island regions in Japan implement curtailment, which controls a part of the generation from renewable energies, to ensure a stable supply of electric power. In the automotive field, research and development of Vehicle-to-Grid (V2G), in which electric power is stored in electric Vehicles (EVs) during periods of low electric power demand and used by the entire power grid during periods of high demand, is in progress. Therefore, we considered using V2G to balance the supply and demand of electric power and reduce the amount of curtailment of renewable energy as much as possible. In this research, CO_2 emissions and changes in the number of days of curtailment were evaluated if V2G, in which renewable energy for curtailment is implemented and used by EVs, is introduced to Tanegashima island, a remote island in Japan, in 2040. Tanegashima island has a population of 27,560 in 2020, and the power source mix is almost 100% solar, wind, and diesel-fired generation. The number of days of curtailment is currently more than 70 days per year.

Since this research assumes the year 2040, electric power demand, the number of automobiles owned, and fossil fuel consumption by automobiles were calculated based on the assumed population of the Tanegashima island. The electric power demand and supply were then calculated hourly for one year by estimating the generation from renewable energies, diesel-fired generation, electric power demand, and the amount of curtailment implemented for the entire Tanegashima island. Fossil fuel consumption was also changed according to the conversion rate of the number of vehicles on Tanegashima island to EVs. CO_2 emissions were calculated from the amount of diesel-fired generation and fossil fuel consumption of automobiles. In addition, Tanegashima island has a large proportion of solar power generation, and the amount of output curtailment during the daytime is very high. Therefore, simulation results were shown by varying two indicators: the switching rate to EVs and the connection rate to the Grid during the daytime. On the other hand, if the connection rate to the Grid during the daytime is high, there is a risk that the demand for electric power during the daytime may be constrained. Therefore, in this research, regardless of the connection rate, it is assumed that charging in excess of the amount of curtailment is not implemented during the daytime.

The simulation results show that when V2G is installed in Tanegashima island, CO_2 emissions decrease as the conversion to EVs progresses. The CO_2 reduction rate was greatest when 20% of the vehicles to be switched to EVs in Tanegashima island and 60% of the EVs were connected during the daytime, resulting in a 2.7% reduction in CO_2 emissions. On the other hand, when vehicles to be switched to EVs exceeded 40%, the CO_2 reduction rate decreased, indicating that sufficient reduction was not achieved. When all vehicles to be switched to EVs in Tanegashima island, CO_2 emissions increased by a maximum of 2.4% from the level before conversion. It was also shown that higher CO_2 emission reductions can be achieved by increasing the amount of renewable energy introduced, but that the CO_2 emission reductions from V2G cannot be fully achieved if the daytime connection rate is low.

Assessing Agricultural Environmental Impacts using EE-MRIO Multipliers

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Mohamed Badr [1], ***Konstantin Stadler*** [1], ***Edgar Hertwich*** [2]

1. NTNU, 2. Norwegian Univ. of Science and Technology

Food production is currently responsible for around one quarter of the global GHG emissions. At the same time, food production needs to increase by 70% to meet the predicted demand of the 2050 population. Recent OECD estimates claim that "*Agriculture's impact on the environment has improved, but there is still much to do*". In this analysis, we answer the question: to what extent has the impact of agriculture changed since 1996. We use EXIOBASE3, an environmentally extended multi-regional input-output model, to derive the impacts per unit output, commonly referred to as environmental multipliers which account for total supply chain impacts (direct and indirect). The analysis observes 14 different agricultural products. We use the impacts: GHG (GWP100), water consumption, and fresh water ecotoxicity along with the stressors: land use crop and employment hours. Multipliers are then adjusted for inflation using FAO producer price indices. Preliminary results indicate that for most agricultural products multiplier values have increased or remained stable since 1996, indicating no significant reduction in agricultural environmental impact per unit output. The analysis also finds that the economic multipliers such as employment hours have generally decreased indicating an increase in efficiency with regards to employment hours per unit output. More so, we find that the value added across the agricultural supply chain has decreased since 1996. Of the impacts/stressors observed, employment hours and Land use were the only extensions that witnessed any improvement since 1996. GHG, water consumption, and fresh water ecotoxicity all witnessed an increase in impact per unit output. We argue that using multipliers which account for total supply chain impacts is more appropriate when assessing the progress of the agricultural industry with regards to its environmental impact. The analysis finds that, when accounting for total supply chain emissions and after adjusting for inflation, no significant improvement has occurred since 1996 with regards to the environmental impact of the agricultural sector.

Comparing Biodiversity Impacts of Recipes across the World

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Yeqing Zhang [1], ***Francesca Verones*** [2], ***Edgar Hertwich*** [1]

1. Norwegian Univ. of Science and Technology, 2. NTNU

What we eat can have a large influence on biodiversity impacts. In recent years, the awareness on diets and associated environmental impacts has been steadily rising. More and more people decide to adjust their diet to alleviate biodiversity impacts. Currently, scenario-based impact assessment, which mainly relies on stylized representations of potential behavioral change, such as full or partial adoption of vegetarian and vegan diets, is widely applied to biodiversity impact evaluation. However, how different individual recipes and the supply chain behind them may impact biodiversity is not well understood.

In this study, we calculate the biodiversity impact of different recipes across the world. Through coupling trade flows from input-output analysis (via EXIOBASE 3) with impact assessments from life cycle assessment, we quantify the biodiversity impact of a diverse set of recipes. By tracing the origin of the food ingredients in a specific cooking recipe for consumption in a specific country, the environmental interventions as well as biodiversity impacts due to the production, consumption, as well as waste disposal of such recipe can be calculated. We use three different dishes (vegetarian, vegan and containing meat) in two countries (Norway and China) comparing and investigating their corresponding biodiversity impact and the underlying causes respectively.

The novelty of our study is that it uses an integrated methodological framework to evaluate the biodiversity performance of a recipe based on the combination of Life cycle assessment and input-output analysis, which allows tracing the impacts through the supply chain. This allows us to assess and compare the biodiversity impact of diverse recipes across different regions and countries with lower uncertainty. It can further be used to compare and evaluate the recipes of diets with diverse underlying supply chains, and analyze what changes are the most influential for reducing biodiversity impacts.

This work is part of the Horizon Europe project RAINFOREST where the ultimate goal of this part of the work is to provide a calculator for the impacts of any food recipe.

Smart Mining Fleet Dispatching System to Reduce Greenhouse Gas Emissions Using Deep Reinforcement Learning

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Da Huo [1]***, Yuksel Asli Sari*** [2]***, Qian Zhang*** [2]

1. *University of Toronto,* ***2.*** *Queen's University*

Artificial intelligence is expected to make future mining operations smarter and greener. To more efficiently dispatch mining haul trucks and reduce fossil fuel GHG emissions, a smart truck dispatching solution is developed in this study using deep reinforcement learning. The proposed algorithm trains each truck in the fleet to make real-time decisions based on loaded material, road traffic, estimated queueing, and maintenance needs. Compared to conventional approaches, the deep reinforcement learning solution improves productivity while reducing over 30% of GHG emissions, and overcomes the difficulty of handling operational randomness such as unexpected changes in fleet size and ore grade. The cost-effectiveness and scaling-up potential of the proposed solution are also evaluated. Comparison with other decarbonization technologies suggests that upgrading existing fleet management systems with AI costs about 200% and 1000% less than fleet electrification and carbon capture and storage, respectively, to reduce the same amount of GHG emissions, and can be rapidly adopted in the near term. These advantages make smart fleet dispatching systems a feasible way to improve productivity and reduce GHG emissions for mining operations before other low-carbon technologies become cost-effective. (Special session: Machine learning & data science applications in industrial ecology)

Using different transport modes: an opportunity to reduce UK passenger transport emissions?

Monday, 3rd July - 12:14: Energy (short presentations) (B0.16 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hugh Thomas [1]

1. University of Cambridge

The transport sector accounted for 34% of territorial UK greenhouse gas emissions in 2019. Furthermore, there has been limited progress in decarbonising the UK transport sector, with sector emissions falling by only 1.6% between 1990 and 2017. Alongside technological shifts and improvements, shifting from the least to the most energy efficient modes of transport is widely recognised as an effective strategy to reduce transport emissions and energy use. This modal shift can lead to rapid and sustained emissions reductions, whilst simultaneously leading to improvements in air quality, reduced urban congestion and population health benefits. To date, many studies and targets only consider modal shifts from one mode to another making it difficult to understand the overall potential impacts of modal shift towards low emitting transport modes.

This study aims to quantify the realistic potential for reducing emissions through modal shift in the UK passenger transport sector. A discrete choice model is used with data from the UK National Travel Survey to determine the least emissions intensive mode of transport that could feasibly be used for each trip. Travel time expenditure, transport mode accessibility, transport network capacities, trip characteristics, and passenger attributes are all considered restrictions that constrain which modes of transport can be used. A sensitivity analysis is performed to identify which factors have the biggest impact on the feasible extent of modal shift. Thus, the actions that should be prioritised to encourage a shift away from emissions intensive transport modes are determined. Total domestic passenger transport emissions can be reduced by 31% without reducing overall mobility or relying on technology development and deployment. This emissions saving is achieved through a 38% reduction in the annual average passenger-km travelled by car and 630% and 210% increases in the annual average passenger-km travelled by cycling and rail respectively. Transport policy should focus on increasing cycling by investing in cycling infrastructure to improve safety and increasing rail use by reducing passenger costs and improving service quality.

A software for recommending weighting method(s) tailored to LCA studies

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Marco Cinelli [1], Grzegorz Miebs [2], Cecilia Askham [3], Andrea Amadei [4], Rosalie Arendt [5], Till M. Bachmann [6], Ayse Bayazit Subasi [7], Luís Miguel Cândido Dias [8], Olivier Jolliet [9], Christoph Koffler [10], Alexis Laurent [9], Masaharu Motoshita [11], Hua Qian [12], Lea Rupic [9], João Santos [13], L. Scherer [14], Bengt Steen [15]

1. Leiden University College, 2. Poznań University of Technology, 3. Norwegian Institute for Sustainability Research, 4. Joint Research Centre, European Commission, 5. Technical University Berlin, 6. European Institute for Energy Research, 7. Istanbul Technical University, 8. University of Coimbra, 9. Technical University of Denmark, 10. Sphera, 11. National Institute of Advanced Industrial Science and Technology, 12. ExxonMobil Biomedical Sciences, Inc, 13. University of Twente, 14. Leiden University, CML, 15. Chalmers University of Technology

Life Cycle Assessment (LCA) is a holistic method to assess the environmental aspects and quantify potential environmental impacts throughout a product's defined life cycle. It is an iterative process covered by ISO standards.

In LCA, weighting enables the identification of the importance levels assigned to various environmental impacts (called impact categories or areas of protection, depending on the level of aggregation). More than 30 weighting methods have been developed over the last decades which may aid the interpretation step in LCA studies. Currently, there is no consensus in the LCA community as to which methods should be applied for given types of study or decision-making contexts.

As part of the UNEP Life Cycle Initiative's (LCI) Global Guidance on Environmental Life Cycle Impact Assessment Indicators (GLAM) project, our working group has developed the WEighting Methods Selection Software (WEMSS), a software for recommending weighting methods for LCA studies. This software contributes to the meta-decision-making problem caused by the large number of weighting methods available nowadays. It assists the user's choice of which weighting method(s) to use for a specified LCA study. This presentation introduces the WEMSS and highlights its four main contributions as follows.

Firstly, WEMSS allows analysts to learn the sequential and dynamic framework shaped to address complex decision-making problems related to weighting in LCA. This is based upon a decision support approach called decision rules, where the modelling framework uses causal connectors in the form of "If the conjunction of requirements on [selected] features is matched, then the recommended method(s) is(are) [list the method(s)]".

Secondly, it comprises the widest (N=35) available database of weighting methods assessed according to a set of 16 criteria. WEMSS includes MCDA (Multiple Criteria Decision Analysis), monetary, data-driven and distance-to-target methods. The criteria relate to the intrinsic and operational characteristics of the methods. The intrinsic ones include, for example, the type of weights that the methods provide (e.g., trade-offs or importance coefficients), as well as the reproducibility of the weights and their uncertainty characterization (e.g., stochastic values). The operational characteristics consider the implementation requirements that the user has. Examples of these characteristics are the geographical resolution of the method (e.g., national, continental), the demonstrated use in case studies, and the potential introduction of biases during the application of the method.

Thirdly, it recommends weighting methods for those case studies for which the analysts' requirements (i.e., desired features) are satisfied.

Finally, even when the description of the decision-making problem is not complete, WEMSS offers a strategy to narrow down the list of suitable weighting methods.

The application of the WEMSS is demonstrated using a set of case studies. It includes the identification of the weighting method to calculate a set of global weights for the UNEP GLAM project, that LCA practitioners can use by default when they do not wish to compute or use other weights.

Analyzing the effect of promoting reusable containers for takeaway food through policies in Taiwan

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hsin-Tien Lin [1]***, Yin-Tsu Peng*** [1]***, Jia-Chun Qiu*** [1]***, Ching-Tuan Su*** [1]

1. *National Cheng Kung University*

The consumption of single-use plastic is increasing rapidly and most of it is used for food packaging, especially under the COVID situation and the growth of online food delivery service. Replacing single-use food containers by reusable containers is a promising solution to the plastic pollution problem. Promoting reusable food containers requires a systematic change for catering industry and consumers, and circular economy businesses that provide reusable container rental service is necessary. Policy also plays an important role to increase incentives and create new norms. In 2023, Taiwan launched a series of policies to promote reusable containers, such as discounts for self-provided containers, restriction on single-use packaging in public offices, and asking chain restaurants to provide reusable container rental services. However, the users of reusable containers are still few and the scale up of the reusable container services is still challenging. Our team run 10 workshops to promote and communicate the policy change with catering service workers and public officers. We also conduct individual interviews with reusable container rental service companies, reusable containers takeaway food providing restaurants, and frequent reusable container users. By the qualitative analysis of the stakeholders interviews, we aim to characterize the driving factors and obstacles of the reusable containers. Our results shows that discounts has a significant positive effect that increase the self-provided reusable container user from 6% to 16%. Meanwhile, the policy restriction on single-use packaging in public offices is to promote reusable containers, but public officers focus mainly on the material substitution of single-use containers rather than reusable ones. Besides, although chain restaurants started to provided reusable container rental services in several stores, the users are still limited to small groups of people. We suggest the policy to include economic incentives to consumers and service providers in addition to restrictions to enable changes and overcoming obstacles.

A systematic comparison of low carbon hydrogen production pathways that align with net zero roadmaps. What are the trade-offs to consider?

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Alice Bennett [1]

1. *University of Cambridge*

To reach net zero we must transition from unabated fossil fuel use to low carbon energy as currently 75% of global greenhouse gas (GHG) emissions are due to energy production and use. Electricity generated from renewable sources will be a key part of the transition, but it is not a complete solution as not all processes can be electrified, and the intermittency of renewable energy increases the storage capacity needed in the electricity grid. Low carbon hydrogen has been suggested as a solution to these issues, but despite momentum for use in the energy sector, the size of the role it will have is uncertain. This is partly due to the technological challenges surrounding hydrogen production, namely whether existing natural gas infrastructure can be repurposed, and doubts over the whole-life inefficiency of hydrogen production and use. However, enabling cost-effective low carbon hydrogen is important in the transition to net zero, even without considering hydrogen for energy use, to decarbonise the current hydrogen sector which is responsible for over 2% of emissions globally.

Our study aims to fill a gap in literature, by systematically mapping the hydrogen production options for the UK that could align with the net zero roadmap, and highlighting the lifecycle impacts of the infrastructure choices available. Four production infrastructure choices have been studied: offshore centralised, offshore centralised using repurposed oil and gas infrastructure, offshore decentralised and onshore centralised. There are also different transmission infrastructure options available which include repurposed existing natural gas pipelines and liquified hydrogen tankers, as well as choices for the energy vector to transport. Each of these have interacting lifetime costs, embedded efficiencies, and GHG emissions that will be modelled utilising existing data where available. Estimating the emissions, cost, and energy impacts of different low carbon hydrogen production routes will help reveal the key trade-offs that should support future decision making for the hydrogen deployment in the UK.

Quantifying the stocks and flows of microplastics across Canada

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Cassandra Sherlock [1]**, *Komal Habib*** [1]

1. *University of Waterloo*

Microplastics (MPs) are pervasive across our ecosystems and societies, posing potential chemical and physical risk not only to wildlife, but to human health. Despite emerging literature regarding the transport, fate, and ecological risk of MPs, few studies have quantified the mass of plastic production and waste emitted into our local economies and environment. Moreover, there is a particular lack of knowledge around the production and environmental emissions of MPs. Due to their small size, MPs are present in our environment in much greater numbers than macroplastics (>5mm). When MPs are diverted and captured, there is no technology to recycle them further contributing to our problematic linear plastics economy. This raises some important questions around how to effectively manage Canada's plastics problem. To address this problem, we plan to quantify the stocks and flows of MPs across Canada.

To investigate this issue, we plan to conduct a static material flow analysis (MFA) for the year 2016, providing a systematic assessment of the flows (the production, consumption, import, loss, and end-of-life treatment of MPs throughout their life cycle) and stocks (mass of MPs collected into environmental compartments i.e., terrestrial, aquatic, and air). MFA is a widely accepted and utilized tool in industrial ecology to map several materials and substances within our society and environment and inform effective management.

Each life cycle stage of MPs will be mapped out through a Sankey Diagram, providing stakeholders with a complete picture of how MPs flow and leak in and out of the system boundary. Data for this investigation will be found through Statistics Canada, industry reports, academic literature, and consultations with industry stakeholders. Based on this data, a model for the MPs value chain will be created with different parameters and criteria influencing the mass of MPs produced, used, and leaked from the system.

Expected results include a baseline measure of the MPs flows and stocks in our system and loss into the environment, and recommend national level management strategies to divert MPs from the environment and manage them through a circular economy.

This work is relevant to the Resources and Materials topic as it addresses utilizing a type of material balance approach to quantify the mass of microplastics flowing and leaking from Canada's economic systems, leading to potential harm to our organisms and humans' health. In addition, this work aims to provide estimates for mass input, flow, and output for microplastics across Canada, which is known to emit a much higher mass of microplastics vs. macroplastics into our environments. The findings of this work will provide suggestions for technological and policy interventions to relevant stakeholders regarding the loss of MPs in our ecosystems.

A novel technique for mapping material and information flow in food traceability systems

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Samantha Islam [1]***, Jonathan Cullen*** [1]

1. *University of Cambridge*

Traceability of food products, ingredients and associated operations are important requirements for improving food safety and consumer confidence. Food traceability systems are complex, encompassing processes, material flow, information flow, techniques, infrastructure, people, and control strategies. Food traceability systems often suffer from inefficiencies in either material or information flow within an enterprise or between supply chain partners. Modelling of system architecture is a visualisation approach that allows multiple parties to collaborate in a system design process, identify its inefficiencies and propose improvements. However, there is little academic research on the ability to use a standard visualisation tool that supports collaborative design and considers both material and information flow for a given food traceability system.

Therefore, the aim of this research is to propose a new visualisation approach that allows supply chain operators to collaborate effectively in the design process of food traceability systems capable of maintaining streamlined information flow, minimizing information loss, and improving supply chain performance. Screening of literature demonstrates that model-based system engineering (MBSE) offers a sound way for visualisation of complex multi-dimensional systems. However, in the food traceability literature, an MBSE-based standardised traceability system modelling approach is absent. This study makes a strong contribution to existing literature by proposing a novel, material and information flow modelling technique (MIFMT), to visualise food traceability system architectures. MIFMT can support common understanding and iterative implementation of effective food traceability systems that contextualize food supply chains at multiple levels and provides opportunity to identify points at where inefficiencies can occur so that actions can be taken to mitigate them.

Further, the proposed tool is applied for quantitative information loss assessment in Bangladesh export shrimp supply chain. The study uses primary data on the supply chain comprising a farm, a depot and a processor. Providing standardised visualisation and quantitative information loss evaluation, the proposed method offers a systematic approach for analysing vulnerabilities in the food traceability system. The results of this approach are used to make specific reengineering suggestions to improve the existing shrimp traceability system in Bangladesh. The method could be applied widely in various food supply chains to support systematic reengineering e.g. blockchain and IoT implementation in existing systems.

Towards automated mapping of global mining land use

Monday, 3rd July - 12:35: New IE developments (short presentations) (B0.13 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tim Werner [1]***, Victor Maus*** [2]***, Laura Sonter*** [3]

1. *The University of Melbourne,* ***2.*** *Wirtschaftuniversität Wien,* ***3.*** *The University of Queensland*

Advances in the quality and accessibility of satellite imagery have prompted rapid growth in research mapping the land footprint of mining. Multiple research teams have recently compiled open datasets with more than 150,000 polygons covering mining activities worldwide. These data help to explain the size, spread and nature of land use challenges linked to global material supply chains. Yet so far, it has only been viable to gather such data through a time-consuming manual process that requires trained analysts to visually recognise and delineate mine areas. Consequently, published updates on global mining land use are limited to approximately every two years. Meanwhile, mines are highly dynamic, constantly changing and expanding into new land. To keep pace with the real-time changes in mine areas globally, efforts to automate the task are needed.

This presentation outlines recent advances in the use of machine learning algorithms to automatically detect mine areas in satellite imagery. Building from this, we will discuss barriers and progress towards automating the global mapping of mine areas. Through a series of mapping case studies, we will also illustrate what levels of geometric and categorical accuracy can be achieved for different types of mine features, and for different parts of the world. Finally, we will discuss the implications of access to timely global mine land use data on broader field of industrial ecology, on governments, and the mining industry itself.

Life cycle assessment of swine breeding and manure management: A case study in Yunlin county, Taiwan

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***Liang-Chun Yeh* [1], *Zih-Ee Lin* [1], *Pei-Te Chiueh* [1], *Cheng-Rui Chen* [1]**
***1.** National Taiwan University*

Animal husbandry is an important agricultural activity with high productivity. In Taiwan, water pollution because of swine breeding and manure management has been a serious issue. To solve this problem and improve circular agriculture, policies have encouraged biogas-power generation from livestock waste in recent years. The aim of this case study is to analyze the potential environmental impact hotspots of pig breeding and compare three manure management. The function unit of a 100 kg pig (fattening pig) serves as a reference for this study. The system boundary includes feed production, farm operation, manure management, and fertilizer substitution. In the study, we compared three pig manure management strategies: untreated wastewater (S1), three-stage wastewater treatment (S2), and biogas center (S3). Livestock farms in Yunlin County, Taiwan, were selected as a case study area.

In the untreated wastewater scenario (S1), manure and urine from pig breeding are not treated. The manure is collected into a pile and directly used as fertilizer. The three-stage wastewater treatment scenario (S2) is a traditional pig wastewater treatment method in Taiwan. Pig manure is collected, followed by solid-liquid separation, anaerobic fermentation, and then aerobic treatment. Most of the treated water from the pig manure is discharged into rivers. The energy and heat will be reused in the pig farms, the wastewater treatment system, and the anaerobic fermentation reaction. In the biogas center scenario (S3), which is promoted by the Taiwanese government, the collected pig manure is directly treated by anaerobic fermentation. The treated manure is transported to farmland for fertilizer application. The energy recycling process is almost the same as S2.

Results show that the feed production stage accounts for around 70% of the total impacts, followed by pig farm operation. Pig manure management has the least impact. Comparing the three manure management strategies, S3 has the highest impact due to wastewater discharge, and S1 has the least impact. When the manure and biogas are recycled in the system boundary, S3 has the most benefits that can compensate for the wastewater discharge impact. However, we suggested that three-step wastewater treatment (S2) is the best solution in the case study area because of avoiding excessive fertilization and reducing the impact of climate change and particulate matter formation on human health caused by NH_3, CH_4, and N_2O emissions.

Sustainable Aquafeeds: Using Aquafarmer Preference to Inform a Multi-criteria Decision Analysis

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ramin Ghamkhar [1]***, Andrea Hicks*** [2]

1. *Associate Consultant of Sustainability,* ***2.*** *Wisconsin*

Aquafeed is a major contributor to the sustainability of food production using aquaculture. Therefore, improving the environmental, economic, and societal performance of aquafeeds provides an opportunity to significantly enhance the sustainability of aquaculture practices, which make up the fastest-growing food sector. Fish meal and fish oil are traditionally the main sources of essential nutrients (e.g., protein and fatty acids) in aqua diets. However, the increase in supply prices as well as limited natural resources (e.g., forage fish) have encouraged some stakeholders to seek alternative nutrient-rich options. This work provides a multidimensional assessment of current and promising future aquafeeds, utilizing multi-criteria decision analysis (MCDA). The considered parameters include cost (e.g., ingredients price), life cycle environmental impacts (e.g., Global Warming Potential), and nutrient inclusion (e.g., protein). The results based on varying stakeholders' perspectives (both survey-based and hypothetical) indicate that the replacements of fish meal with plant-based soybean meal and fish oil with plant-based canola oil are the most favorable alternatives among the investigated diets to enhance the overall aquafeed performance in aquaculture food production.

Current and future key factors for the environmental performance of plastic packaging waste management

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Monday, 3rd July - 17:45: LCA and circularity (B0.25 KOG)

Sarah Schmidt [1], ***David Laner*** [1]

1. *Research Center for Resource Management and Solid Waste Engineering, Faculty of Civil and Environmental Engineering, University of Kassel, Mönchebergstraße 7, 34125 Kassel, Germany*

For mitigating the climate crisis, an extensive transformation of material and energy systems is needed. This transformation is likely to affect various sectors directly or indirectly. Among others, the environmental performance of plastic packaging waste management is expected to be affected, for example by decreasing credits for the provision of recycled materials or recovered energy. Although plastic packaging is often criticized as a symbol for the so called make-use-dispose economy, plastic is expected to remain a popular packaging material because of its low weight, low costs, good processability, and customizable features. Therefore, the development and optimization of sustainable plastic packaging waste management strategies remains a critical task also with respect to the ongoing transition of material and energy systems towards higher levels of circularity. The aim of our research was to assess the current and potential future performance of plastic packaging waste management in Germany in view of an extensive transformation of material and energy systems in terms of environmental impacts, health impacts and resource depletion issues and to identify key factors for future optimization.

The current environmental performance of plastic packaging waste management in Germany was evaluated by performing life cycle assessment (LCA). To account for anticipated extensive transformations of material and energy systems, the background system of the LCA model was adapted to prospective changes based on the output results of the integrated assessment models IMAGE and REMIND under consideration of a limitation of global warming to 1.5 °C. Based on the adapted life cycle inventories, LCA scores and sensitivity ratios were calculated for the years 2025, 2030, 2040, 2045 and 2050 to identify potential trends regarding the future development of the environmental performance of plastic packaging waste management and its key factors. Key factors for the environmental performance were identified by means of perturbation analysis. It was shown that plastic packaging waste management in Germany is associated with environmental benefits in all considered impact categories and time steps. Although net environmental benefits of plastic packaging waste management persist over time, the anticipated transformation of material and energy systems results in a decrease of the observed benefits. The results of the prospective LCA highlight that potential measures for improving the environmental performance of plastic packaging waste management should focus on the identified key factors, such as separating plastic packaging waste from the residual waste (in households or in waste treatment facilities) as well as increasing the quantities and qualities of recycled plastics. The present study highlights the utility of fine-grained analysis of environmental performance mechanisms for waste management systems in view of changing boundary conditions using the example of plastic waste management. In the future, further case studies are needed to enable sound decision support on strategies for environmentally robust waste management in view of dramatic anticipated changes in material and energy systems.

Trade-offs between material efficiency and environmental performance for managing plastics packaging waste

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:28: Scenarios (short presentations) (B0.31 KOG)

John Laurence Esguerra [1], *Annica Carlsson* [1], *Stefan Anderberg* [1], *Joakim Johansson* [1]

1. Linköping University

The single-use function of plastic packaging generates a continuously increasing input to the waste management system leading to sustainability challenges. In response, several management strategies along the plastic value chain are proposed including improvements on product design, source-separation, mechanical and optical sorting, and further downstream material recycling. However, in some countries like Sweden, these strategies are often implemented in isolation without considering their combination effects on the performance of the entire plastic value chain. Moreover, the corresponding assessments of these strategies are often limited to material efficiency (i.e., recycling rate) thus overlooking the potential trade-offs with environmental performance. Hence, this study aims to assess the combination effects of different management strategies for plastic packaging in Sweden in terms of both material and environmental dimensions. Over 700 scenarios involving different combinations of management strategies were modeled and assessed through life cycle assessment. The results show that upstream strategies such us polymer restriction especially for food packaging (i.e., limiting to polyethylene terephthalate and polypropylene) lead to higher recycling rates and better environmental performance. In contrast, further downstream material recycling strategies show more apparent trade-offs, especially between recycling rates and environmental impacts related to toxicity. Recommendations for the combinations of management strategies for plastic packaging, which can increase recycling rates and reduce environmental impacts, are presented and discussed.

Digital food sharing and food insecurity in the COVID-19 era

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tamar Makov [1], ***Tamar Meshulam*** [1], ***Alon Shepon*** [2]

1. *Ben Gurion University of the Negev,* ***2.*** *Tel-Aviv University*

Sharing food surplus via the digital sharing economy is often discussed as a promising strategy to reduce food waste and mitigate food insecurity at the same time. Yet if and how the global pandemic has affected digital food sharing are not yet well understood. Leveraging a comprehensive dataset covering over 1.8 million food exchanges facilitated by a popular peer-to-peer food sharing platform, we find that UK activity levels not only rose during the Covid-19 pandemic, but outperformed projections. A potential explanation for this growth might be the rise of food insecurity during the pandemic. Yet examining the sociodemographic characteristics of platform users, average user activity and food exchanges before and during the pandemic, we find no compelling evidence that the platform's pandemic-era growth results from large influx of food insecure users. Instead, we posit that the growth in digital food sharing relates to lifestyle changes potentially triggered by the pandemic.

Streamflow uncertainty to mean areal precipitation: impact on precipitation station selection

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Hakkwan Kim [1], ***Jung-Hun Song*** [1], ***Solhee Kim*** [1], ***Kyo Suh*** [1]

1. *Seoul National University*

Precipitation is one of the major inputs for hydrological models. The spatial variability of precipitation is often considered to be a significant source of uncertainty for hydrological models. In many cases, the precipitation records are spatially aggregated to calculate mean areal precipitation (MAP), and the MAP is fed to hydrological models. Studies have employed different methods in selecting representative precipitation stations to derive the MAP. However, the performance of hydrological models has not yet been sufficiently evaluated to assist in selecting MAP calculation methods. This study investigates the influence of different MAP calculation methods on streamflow simulations. Three other ways, (1) Nearest Neighbor, (2) Thiessen Polygon, and (3) Homogeneous precipitation regions, were applied to select representative precipitation stations for the MAP calculation. A lumped conceptual rainfall-runoff model with five parameters (FPHM) was used to investigate the sensitivity of model performance to the MAP methods. The FPHM was applied to 41 watersheds throughout South Korea. The FPHM was calibrated for each precipitation data set with the AMALGAM optimization method and the objective function, Kling Gupta Efficiency (KGE). The difference in terms of estimated MAP and streamflow in this study confirmed that evaluation of precipitation station selection is necessary before hydrological modeling. The results showed that the uncertainties could explain a large part of the errors in hydrological modeling in precipitation estimates. These errors are a significant factor limiting the performance of the rainfall-runoff simulation.

Consumption-based Regional Emissions Budgeting Framework - A case study of the South Yorkshire

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Ling Min Tan [1], *Vania Sena* [1]

1. The University of Sheffield

Monitoring of emissions against an established baseline is essential in reducing emissions. Greater monitoring capability leads to a more robust evidence base on which to make more informed decisions on emission reduction measures. In the UK, a territorial based accounting system is commonly used to account for all direct emissions due to activities taking place within sub-national geographic boundaries. However, such approach does not account for in-direct emissions incurred from shipping and generation of energy consumption in production processes. Similar to territorial emissions, a production based accounting (PBA) system allocates emissions based on where the goods and services are produced. In contrast to PBA, a consumption based accounting (CBA) system offers an alternative by allocating emissions to the consumers based on final consumption of goods or services. CBA includes all direct and indirect emissions in the lifecycle and supply chain of products or services consumed.

This project seeks to address the challenges of assessing regional emissions in order to evaluate the scale of projected impact and the effectiveness of emissions reduction interventions across the region. To support evidence driven decision making, a Regional Emissions Budgeting Framework (REBF) is proposed as a dynamic planning tool for managing regional emissions audits and monitoring progress towards decarbonisation targets. To investigate regional consumption-based emissions, an environmentally extended input-output (EEIO) model is developed to analyse spending from households and government, and business capital expenditure, based on financial flow data from national and regional economic accounts. Hence, the key challenge of performing CBA on a regional level is to derive the EEIO of sub-national trade flows for accounting the embedded emissions of goods and services consumed by a local economy, and their upstream carbon footprint from the supply chain. This provides a baseline value for regional CBA, which is then used to generate future emission pathways and predict the impacts of carbon reduction scenarios, which are tailored to be more realistic for the region based on local policies and economic structure.

Here in this case study, we demonstrate the development of an EEIO for the South Yorkshire region in England, which consists of four local authorities, each with their own administrative management. The REBF is designed to be used as a dynamic planning tool that can quantify the short- and long-term socio-economic and environmental impacts of policy measures on the region. With involvement and inputs from the local governing bodies, the collective objective for building the REBF is to develop a unified and consistent process for monitoring regional emissions and carbon budgeting across all local authority areas in the region. To achieve this, a streamlined workflow in a single timeline is needed to standardise the regional approach to CBA and carbon budgeting based on projections of potential carbon reduction scenarios for all areas. The novel model will use the theory of change to understand the connections among economic sectors, urban and rural environments and potential feedback effects. In the way forward, it will explicitly model the relationship between the built environment, food production systems and land management, which will allow the stakeholders to follow the behaviour of key regional indicators over time, and then to evaluate the effectiveness of interventions implemented.

Water-Energy Nexus Tool: an energy assessment model for the wastewater treatment plants

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Shalini Nakkasunchi [1], ***Neil James Hewitt*** [2], ***Oliver Heidrich*** [1], ***Caterina Brandoni*** [2]

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Relation between wastewater and energy are highly significant and complex since decades. Globally, up to 5% of the energy, especially electricity is consumed by the wastewater treatment plants (WWTPs) (McCarty et al., 2011). Even today, major of this energy is generated from the fossil fuels, which in turn leads to the indirect greenhouse gas (GHG) emissions. Alongside this, the WWTPs have potential to recover energy from the wastewater and sludge generated from wastewater treatment (Sarpong et al., 2019; Sun et al., 2020). Integrating these with the renewables like solar and wind (Ali et al., 2020; Yang et al., 2020) can generate the total or partial energy required by the WWTPs and simultaneously reduce the GHG emissions associated with the energy supply from fossil fuels (through grid electricity, natural gas and oil consumption). Considering the nature of these renewable sources, the recoverable energy from wastewater and sludge can be termed as the sector specific renewable energy and the energy generated from the other renewables like solar and wind as non-sector specific renewable energy. Following this, a review of research articles on identifying a model and tool to perform energy assessment of the WWTPs was conducted (presented in (Nakkasunchi et al., 2021)). None of the tools or models could perform the energy assessment of the WWTPs including energy accounting, energy recovery from wastewater and sludge, and renewable energy generation on a single platform. Hence, a framework "Water-Energy Nexus Tool (WENT)" was developed for the WWTPs by integrating different relevant models from literature in MS Excel Environment for user friendly and easy accessibility. This framework provides flexibility to assess the energy demand and techno-economic feasibility of the renewable energy generation at the WWTPs. The developed framework was tested against the four wastewater treatment plants in Murcia (two plants), Fano and Norther Ireland. Based on the results obtained from these case studies and literature data, recommendation on reducing the GHG emissions of the WWTPs are proposed for the WWTPs.

LIFE CYCLE ASSESSMENT OF DIMETHYL ETHER produced from algal biomass

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***vaibhav Panchore** [1], **Raja Chowdhury** [2], **Sachin Kumar** [2]*

***1.** Indian Institute of Technology, Roorkee, **2.** Indian Institute of Technology, Roorkee, India*

A life cycle assessment approach was conducted to access the greenhouse gas emissions from dimethyl ether (DME) production using algal biomass. It was assumed that transportation fuel (diesel) would be replaced by DME. Hence, the production of diesel was taken as the reference flow. Changes in engines, transportation, etc., for the introduction of DME were not under the scope of the study. Syngas produced from gasification was used to produce DME by catalytic intervention. In this study, algal biomass produced during wastewater treatment was harvested and used for syngas production. The foreground processes of the algal biomass production was as follows: (i) wastewater treatment of algae in an algal pond,(ii) algae harvesting by centrifugation and filtration; (iii) excess algal biomass produced was fed in a gasification reactor, (iv) DME production, (v) DME and methanol separation. The background process was electricity production. GHG emission from the Indian electrical grid was taken to model the same. For estimating GHG emissions from the electricity a large number of coal based plants were taken and their load factor was considered for estimating the GHG emission. Except load factor, type of coal used (lignite vs bituminous) for each plant was determined through soft computing techniques. Later, a weighted average emission factor GHG emissions for Indian coal power plant was estimated. This emission factor and other emission factors for GHGs for other types of electricity production were used to estimate the GHG emissions from the Indian electricity grid. DME production was estimated through equilibrium chemistry, whereas syngas composition was estimated through an optimization routine using experimental data of algae gasification available in the literature. Energy consumption for foreground processes was taken from literature. From 1 MLD wastewater, it was estimated that 584.685 moles of DME and 6.09 moles of methanol could be produced. GHG emissions (CO_2 equivalent) per MJ of DME production was 1.018 kg CO_2/MJ. Allocation by the energy was used for allocating GHG emissions to the DME and ethanol.

Carbon Footprint of Household Energy Use in the United States

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Benjamin Goldstein [1]***, Joshua Newell*** [2]***, Dimitrios Gounaridis*** [2]

1. *McGill University,* ***2.*** *University of Michigan*

Heating, cooling, and powering homes accounts for nearly 20% of territorial carbon emissions in the United States. Here, we use data on 93 million individual households to model energy use and carbon emissions of homes across the United States and chart a decarbonization pathway for this sector in line with the 2030 and 2050 Paris Agreement Targets. We find that per-capita emissions in affluent neighborhoods are 25% higher than emissions in poor neighborhoods, but that this gap can grow to a factor 12 between proximate neighborhoods in extreme cases. Although heating system and climate explain some of this difference, floor area explains most of the gap in emissions between affluent and poor neighborhoods. Scenario analysis shows that the existing housing stock can meet the 2030 Paris Target through grid decarbonization, but that aggressive rates of deep energy retrofits and deployment of distributed low-carbon energy systems are also needed to meet the 2050 goal. Results also suggest that dense settlement patterns for new construction will reduce energy demand and accelerate decarbonization for the tens of millions of homes that will be built in coming decades.

The Potential of Controlled Environment Agriculture in Canada: A life cycle assessment of container farming and aquaponics

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Goretty Dias [1]***, Carolina Romero Pereira*** [1]***, Gayathri Valappil*** [1]***, Jeffrey Wilson*** [1]***, Christine Moresoli*** [2]

1. *School of Environment, Enterprise, and Development, University of Waterloo,* ***2.*** *Chemical Engineering, University of Waterloo*

Controlled environment agriculture (CEA) is increasingly being viewed as a viable option to increase food security in the face of climate change, particularly by offering protection from changing weather patterns and other undesirable external conditions. Additionally, CEA may allow food production expansion without requiring large amounts of land and water. Globally, the Covid-19 pandemic and war have disrupted food supply chains and shown the vulnerability of our food systems to geopolitical risk. In Canada, a cold climate country which imports a substantial amount of fruits and vegetables saw a supply interruption of these foods during Covid restrictions and with recent extreme weather conditions, prompting more serious consideration of the expansion of CEA for food security and stable supply. This transition to CEA fruits and vegetables needs to be done in a sustainable way, but the environmental performance of these systems in Canada, and other cold climates have yet to be explored in depth.

In this study, we used life cycle assessment (LCA) to evaluate the environmental performance of two CEA operations in Canada: 1) a container farm, which uses retrofitted shipping containers to produce leafy greens; and 2) a small-scale decoupled aquaponics system, which combines recirculating aquaculture with hydroponics to produce both fish and leafy greens.

Both systems showed higher global warming potential (GWP) than conventional forms of fish and leafy green production, mostly due to the large, and predominantly non-renewable electricity usage for: 1) lighting required for plant growth; and 2) heating and cooling for maintaining constant temperature conditions in the extreme temperatures encountered in Canada. GWP was 10-50 times higher for leafy greens produced in the container and aquaponics systems, respectively, compared to 1 kg of field greens transported 1500 km by truck. However, water use was seven times lower for the container farm than for field production of leafy greens.

An analysis targeting energy efficiency improvements and the use of renewable energy sources showed that the best alternatives were wind energy, LED lighting, and insulation, which reduced GWP in the aquaponics system by 97%; however, a life cycle cost analysis showed that the best eco-efficiency (GWP vs. cost) was achieved with the LED lighting alone, or on-site biogas heating paired with wind energy and efficiency measures.

CEAs have the potential to reduce water and land use, and increase fertilizer use efficiencies; but if CEA in northern climates are to be part of a transition to more sustainable food systems, reducing energy use and its source need to be considered through industrial ecology and other scientific approaches, such as: designing buildings/containers to optimize natural light and energy efficiency; using renewable energy sources and/or waste heat; selecting climate appropriate (heat/cold resistant) crops and fish, in order to reduce the energy intensity of the operation.

Nature-positive LCA of Production and Consumption Systems

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Mathilde Vlieg [1], ***Delwyn Jones*** [2]

1. MalaikaLCT, 2. The Ecquate Evah Institute, Tamborine Mountain QLD

Over a half-century, production and consumption systems have adopted robust Life Cycle Assessment (LCA) methods and international standards for calculating sustainability impacts in quality control and product eco-labelling. While emerging Cradle to Cradle, Blue Economy, Circular Economy and Nature Positive assessments focus on bringing positive news about products, services or buildings, Life Cycle Impact Assessment (LCIA), however, still only measures negative damage and loss outcomes. These positive methods could benefit from LCA's robust background, conversely LCA could incorporate benefits assessment.

The authors' Life Cycle Benefit Assessment (LCBA) methods define and quantify beneficial outcomes and gain of tiny integrated circuits to global supply chains. Typical LCIA is depicted covering zero to gross damage versus LCBA from zero to capacity gain. The work reviews concepts, theory and practice of ReCiPe LCIA alongside LCBA.

LCIA categories cover human health, ecosystems and resource loss from air, land and water pollution forcing climate change as well as land use change and mining depleting biodiversity, freshwater, minerals and fossil fuels. LCBA categories include human wellness, habitat capacity and resource cycling gain due to clean air, land and water, relaxing climate change. Gain is also due to sequestering emissions, purifying effluent, regenerating land use biodiversity and freshwater plus recycling mineral and fossil fuel feedstock resources.

The work illustrates unstainable, sustainable and regenerative development in charts of net-damages and net-benefits developed by Industrial Ecology (IE) master's students under the author's supervision. Charts show how preferences may differ when benefits are not excluded. This offers a transformational step in understanding how to transition toward sustainable consumption-production systems. They also show how benefits can be communicated in a transparent way alongside of damages, without risking double counting or greenwashing.

Case studies show LCIA of a state capital city 100% post-consumer recycled (PCR) paving aggregate lacked capacity to model or show recycling had any net-positive gains. LCIA of council paving for a state capital city main road are then tabled showing damage outcomes from quarried aggregate compared to 100% PCR aggregate. For another state capital city's PCR aggregate paving both damages and benefits are tabled which show many very significant land use and human wellness benefits from reclaiming instead of landfilling scrap and quarrying rock.

Nature Positive outcomes are only evident in the last case study as they show benefits and damages, whereas the first one shows only worse losses from primary aggregate and the second only shows damages.

The authors' case studies employing methods to count benefits versus damage show losses compared to gains. They demonstrate net damages as well as net benefits considering unstainable, sustainable, and regenerative development. Preference can change considering benefits. Also it shows how benefits can be communicated alongside damages to avoid double counting or greenwashing while inspiring action and confidence.

Would you Change your Travel Mode if you know its Carbon Footprint?

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Erin Bulson [1], ***Wissam Kontar*** [1], ***Andrea Hicks*** [2], ***Soyoung Ahn*** [1]

1. University of Wisconsin-Madison, 2. Wisconsin

The echoing environmental toll of the transportation system alarms for drastic needs to move beyond carbon-intensive modes of transportation into more sustainable ones. With the rise of emerging modes of transportation, this transition is more promising than ever. However, the prevailing travel behavior induced by a car-centric transportation system hinders this transition.

In this work, we take a travel-centric approach to promoting the transition away from carbon-intensive modes of transportation by displaying travelers' carbon footprint for each of their trips. Towards this end, a carbon calculator, as a function of trip distance and well-to-wheel LCA data, was developed and embedded into a website format. Inside the website, users would insert their trip distance, and the calculator outputs the carbon footprint of the trip if it was to be done through seven different modes of transportation: car (gasoline), car (hybrid), car (electric), bus, electric bike, conventional bike, and walking. The calculator also outputs the equivalent of CO2e as cheeseburgers for a more intuitive display.

A recruitment process was launched in Jan 2023, whereby users would use this calculator for their daily trips and record what mode of transportation they intended to use before looking at their carbon footprint and what they end up using afterward. The analysis shows that 48% of respondents had at least one modal change after using the calculator, and 16% of trips had a modal shift away from carbon-intensive modes. Further analysis reveals characteristics of travelers who were willing to change their transportation mode and how this relates to aggregate environmental benefits.

The overall goal of this work is to understand how travelers respond to being exposed to carbon-footprint information. This serves as a step forward in realizing a sustainable transportation system.

The rapid energy transition and resource extraction lock-in

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

John Mulrow [1]***, Kendrick Hardaway*** [1]***, Miriam Stevens*** [1]***, Thomas Maani*** [1]

1. *Purdue University*

Introduction:

With signs and symptoms of climate change continuing to worsen, it is widely accepted that A) our economic systems must shift away from carbon-emitting sources of energy and B) this transition must be rapid. In 2022, the US congress passed two major spending bills aimed at facilitating such a transition through expansion of renewable energy and electric vehicle charging infrastructure. The EU is set to enact similar funding programs, and furthermore has deregulated renewable energy installations to encourage adoption.[1]

Previous research has shown that the trade-offs between infrastructure build-out and enablement of the energy transition are worth it in a direct sense. Mulrow and Grubert[2] determined that the emissions embodied in a rapid scale-up of EV charging stations would represent just 1% of the emissions reductions made possible through a more rapid shift away from combustion engine vehicles, and similar conclusions exist about the overall energy transition.[3,4] There is also substantial research to show that the materials required for such a transition are available.[5,6] Thus, an energy transition is both physically possible and environmentally justified.[7]

Through our research, we ask about an additional factor that is seldom examined in sustainability discourse: the *rate* of infrastructure turnover and installation. Based on previous studies we have shown that *speed* is a factor of concern in environmental assessment of transportation systems.[8] The higher the speed of the transition, the greater the extractive capacity (materials per unit time) would be needed. We are thus motivated to ask: Could we end up with large mines whose production capacity extends beyond the transition, locking us into continued high-volume resource extraction? How would the environmental impact of a faster transition differ from a slower one?

Methods:

We first establish a method for defining and measuring the extraction rates required to enable a rapid transition of vehicle fueling and electricity generation/transmission infrastructure. Here, we build on our existing work forecasting EV infrastructure scale-up requirements.[2] Then we pair this information with existing data on material intensities and established knowledge about the useful life of various critical material extraction facilities, providing an estimate of the total resource extraction enabled by the transition. We build a probabilistic model of total material footprint enabled by the energy transition, meant as a proof of concept regarding the importance of energy infrastructure transition rate.

We conclude by examining other feedback effects that may arise from a high-speed energy transition: Can proposed limits to extraction in line with emissions goals accommodate the demand needed for a rapid energy transition? What impact might it have on other planetary boundaries like biodiversity? We validate the analysis using existing data on critical materials for the energy transition in a US context.

Results and Discussion:

Accepting a rapid transition may lead to an unsustainable level of resource consumption and demand lock-in, compared to a slower one. It could also lead to further delays in taking united, global-scale policy action to set and enforce resource demand limits. These second-order effects alone represent reasons to be skeptical, not about the need for energy transition, but about its rapidity.

Our preliminary results suggest that a slow transition, coordinated with economic degrowth and reduction in total energy requirements, is a more robust and consistent goal for enabling equitable sustainability.

Low-carbon hydrogen production, integration, and impacts in oil refineries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Erik Lopez Basto [1], *Andrea Ramirez* [1], *Gijsbert Korevaar* [1]

[1]. *Technical University Delft*

This research evaluates the implementation impacts of the production of low-carbon hydrogen in oil refineries. Two Colombian refineries are used as a case study, for each refinery, solutions pathways are identified according to the complexity and geographical location. The methodology consists of a combination of a system analysis optimization with multi-criteria decision analysis. The system analysis uses Linny-R, a mixed integrated linear programming (MILP) software package developed by Delft University of Technology. The system analysis describes processes and runs scenarios. A multi-criteria decision analysis method based on the Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) together with a Best Worst Method (BWM) provides the criteria ranking.

Short-term (2030) alternatives include hydrogen produced by Steam Methane Reformer units (SMR) with CO_2 Capture Storage and Utilization process (CCSU) and hydrogen produced by several renewable electricity sources. Long-term (2050) alternatives include SMR units with more efficient CCSU, more efficient hydrogen electrolysis, biomass, petcoke gasification, and methane pyrolysis. The TOPSIS and BWM assess process alternatives under technological, environmental, economic, and deployment criteria, based on literature reviews. To define the relevance of each criterion, structured interviews are performed with key representatives of several stakeholder groups.

As a result, we obtain insights into how to implement low-carbon hydrogen in oil refineries. This insight is shown as a ranking of alternatives generated for each type of refinery in the short and long term to achieve the committed CO2-cutting emission goals. This research also provides guidelines to evaluate the future development of decarbonisation in oil refineries.

Life cycle assessment of demand-side management in energy systems: A system-wide perspective

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Benedikt Nilges [1], ***Christiane Reinert*** [1], ***Niklas von der Aßen*** [1]

1. Institute of Technical Thermodynamics, RWTH Aachen University

For the transition towards low-carbon energy systems, electricity supply and demand must be synchronized by alternatives to conventional regulation of fossil-based power plants. Alternative options to synchronize supply and demand are electrical storage and residential and industrial demand-side management (DSM). For the environmental assessment of DSM, the holistic method of life cycle assessment (LCA) can be applied, which quantifies the environmental impacts of a process or product over the complete life cycle. In literature, hourly average or marginal emission factors of electricity generation are used to allocate the time-dependent environmental impacts of electricity generation to the flexible operation by DSM. However, hourly average and marginal emission factors of electricity generation are calculations at a specific time and place of the energy system, based on the assumption that the process applying DSM does not influence the energy system.

We analyze the environmental impacts of DSM while considering the interaction between the process applying DSM and the energy system. Our case study is the flexible operation of the switchable chlor-alkali electrolysis in the German energy system. The switchable chlor-alkali electrolysis is an energy-intensive process in the chemical industry, which can apply DSM by switching between two operation modes with different electricity consumption. We integrate the chlor-alkali electrolysis into a spatially and temporally resolved optimization model of the German energy system. The optimization model determines the operation of the switchable chlor-alkali electrolysis and the energy conversion technologies by minimizing the total operational cost of the overall system. We conduct a life cycle assessment for the flexible operation and for the steady-state operation using the conventional operation mode. The environmental impacts of the flexible operation are normalized to the environmental impacts of the steady-state operation, which are determined by using hourly average emission factors of the electricity generation.

The goal of our study is to compare two cases for calculating the environmental impacts of the flexible operation: In the first case (A), the environmental impacts of the flexible operation are calculated using the hourly average emission factors, representing the state-of-the-art calculation. In the second case (B), the changes in the environmental impacts of the overall system due to the flexible operation are subtracted from the environmental impacts of the steady-state operation. Thus, the consequences due to the interaction of the switchable chlor-alkali electrolysis and the energy system are fully allocated to the flexible operation of the switchable chlor-alkali electrolysis.

The analysis shows that the environmental impacts of the flexible operation normalized to the steady-state operation differ significantly when assessed by using hourly average emission factors (case A) or the allocation of the consequences (case B). The differences between the environmental impacts of the two cases (case B - case A) range between a reduction of -71% (ozone layer depletion) and an increase of +14% (ionizing radiation) in all impact categories. The different results in the assessment of the flexible operation show that using average hourly emission factors for DSM may lead to neglecting relevant system interaction. Therefore, we conclude that average hourly emission factors should be used cautiously when assessing DSM of energy-intensive processes.

Levelized cost of inter-city electric vehicles charging option in China

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

HAO HAN [1]

1. City University of Hong Kong

China has revealed its ambition to achieve carbon neutrality via facilitating industrial transformation, especially in the transportation sector. Promoting private electric vehicle (EV) consumption and establishing supportive infrastructure has become one of the major tools for the state to achieve this goal. However, such broad-scale transformation requires radical shifts in charging infrastructure along the road network. Despite the increasing prevalence of intro-city charging stations, especially in south-eastern China. Studies regarding the feasibility and effectiveness of building inter-city EV-supportive infrastructure remain silent. Moreover, being a country with unbalanced developmental status, the feasibility and effectiveness of EV transformation in north-western China remain largely unknown.

Here, we attempted to model and compare the potential cost of building the inter-city charging infrastructure nationwide, in particular, with a focus on north-western China. We gathered extensive market data on the equipment and labor cost in building and maintaining the commonly used charging stations and other facilities. Given the rapid technological development of EV battery capacity and charging options, we also factored in the possible scenarios such as battery-swap and plug-in hybrid technology. The result aims to reveal the estimated cost of building and maintaining EV-supportive infrastructure in futuristic scenarios. The findings inform the state and local authorities in developing infrastructure-building policies and optimizing resource efficiency for facilitating private EV consumption.

Prediction of the end-of-life NCM batteries considering elongation of lifespan in China until 2035

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wenjing Gong [1]***, Ichiro Daigo*** [1]
***1.** The University of Tokyo*

Global climate change has drawn great attention because it threatens human safety and ecosystem health. In China, CO_2 emissions in transportation are about 9×10^8, accounting for 9–10% of greenhouse gas emissions. And new energy vehicles (NEVs) are essential to reduce greenhouse gas (GHG) emissions and improving energy security. Among NEVs, battery electric vehicles (BEVs) are getting more attention because they emit less GHG through the lifecycle than plug-in hybrid electric vehicles.

As BEVs' core component, power batteries' capacity has also increased significantly each year. Especially the development trend of NCM (from NCM111 to NCM 811), which contains less cobalt than nickel and high capacity, and NCM battery vehicles in BEVs reached 65% of all batteries in 2020. Although some studies have calculated the end-of-life quantity of retired batteries, few have focused on NCM batteries, which are dominant in the market. Also, there will be an evolution trend among different NCM battery types, influencing the recycling and recovery profit. Besides, most researchers consider lifespans a constant over time, but the lifespan distribution may differ as technology improves.

In this research, an elongation of lifespan was applied to calculate the end-of-life NCM batteries in China until 2035, using the primary sale data collected from the China Association of Automobile Manufactures. And according to the Road Map of Energy Conservation and New Energy Vehicle Technology (CSAE, 2020), the sales of NEVs exceed 4% of the total vehicle sales in 2020, 20% in 2025, and 40% in 2030, and the sale plan of total vehicles in China is 30, 35, and 38 million in China, respectively. And we supposed that the total number of vehicles in 2035 will be 41 million, which will contain 50% of NEVs. Assuming that the total sales of NEVs and BEVs in the year between two adjacent time nodes continuously increase, the total sales of BEVs in 2022–2035 can be estimated. Among the BEVs, NCM vehicle sales increased from 78 thousand to 1.8 million from 2015 to 2021. To predict the number of NCM vehicles, we assume it will occupy 65% of the total amount of BEV until 2035.

However, the market share of NCM battery technologies is uncertain in the future because battery producers are seeking to replace costly cobalt with nickel, which has led to an evolution from NCM111 to NCM523, NCM622, and NCM811 batteries, and the cell energy densities assumed here from 177 Wh/kg for NCM111 to 207 Wh/kg for NCM811. Here, we applied three scenarios of the future NCM market penetrations in China to investigate different development scenarios, including Slow Upgrade Scenario (S), Moderate Upgrade Scenario (M), and Fast Upgrade Scenario (F).

According to CASE, with technical advances, the average lifespan of NMC batteries, which is 8 years before 2020, would increase to 10, 12, and 15 years in 2020, 2025, and 2030, respectively, and it was assumed as 17 years in 2035. A Weibull lifespan distribution was adopted to parametrize the lifespans.

This research will reveal the development of NCM batteries, including different evolution scenarios and elongation of lifespan patterns. Besides, the recycling profit can be further calculated based on the end-of-life quantity result. Finally, it may help government make a better decision by preparing for the huge amount and the major battery types for end-of-life batteries in advance.

The emergy footprint of a city: comparing supply- and use-extended input-output models for the case of Vienna, Austria.

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Oleksandr Galychyn [1], ***Brian Fath*** [2], ***Dominik Wiedenhofer*** [3], ***Elvira Buonocore*** [4], ***Pier Paolo Franzese*** [4]

1. *Finnish Environmental Institute (SYKE),* ***2.*** *Towson University,* ***3.*** *University of Natural Resources and Life Sciences (BOKU),* ***4.*** *Parthenope University of Naples*

The design of environmental extensions in the input-output analysis is based on the user-side perspective and only focuses on commercial energy supply and use, which implies that its spatial and temporal boundaries are limited to technical energy extraction and use. Moreover, the literature that discusses donor-side perspectives to supply and use-extended footprint models are in their infancy. This study introduces an emergy-evaluated supply-extended and use-extended carbon footprint models for the The City of Vienna then compares and assesses differences in results for their empirical and conceptual implications. Our results show that the ranking of footprints of final products categories are sensitive to the evaluation method and that products of extractive and manufacturing industries (agricultural and chemical products) differ by more than 10% depending on whether emergy or carbon evaluation is chosen. The the emergy-based comparison further reveals that for products of extractive industries difference between use and supply extension results can be more than 20% as opposed to carbon-based comparison with the difference between supply and use extension results for services not even amounting to 5%. We, then discuss conceptual differences between emergy and traditional carbon-evaluated extension designs and conclude that a more accurate estimation of the total environmental burden of each sector in an urban economy can be archived in the first step of the allocation procedure used in emergy-evaluated use-extension design (allocation of direct energy use of fuels to final consumption to households, government, capital formation, and exports) is added to emergy-evaluated supply-extension results. Such use of these models provides a the basis for a comprehensive understanding of environmental support for production

processes and economic activities and, therefore, can assist policymakers in

assessing the implication of their local decisions on the larger scale of socio-economic

and life-support systems.

Towards a Circular Economy for PET bottles in the US - a System-Dynamics Approach

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tapajyoti Ghosh [1], ***Taylor Uekert*** [1], ***Julien Walzberg*** [1], ***Alberta Carpenter*** [1]

1. National Renewable Energy Laboratory

The United States generates the most plastic waste of any country. Along with that GHG emissions from the global plastic economy are expected to increase to 15% of the global carbon budget by 2050. It is imperative that plastic recycling is made a reality to reduce both plastic pollution in the environment and GHG emissions. A portfolio of end-of-life strategies must be implemented to minimize environmental impacts and retain valuable plastic material, but it is challenging to compare options that generate products with different utility and lifetime. Plastic use reduction, reuse and recycling are thus increasingly important, but making informed policy and research decisions within this space can be challenging given the diverse range of available solutions. The novel analysis framework, Plastic Parallel Pathways Platform (4P) has been equipped with consequential life cycle assessment, techno-economic analysis, and a plastic circularity indicator to estimate the greenhouse gas (GHG) emissions, circularity, and cost of polyethylene terephthalate (PET) down-cycling to lower-quality resin, closed-loop recycling to food-grade PET bottles, up-cycling to fiber-reinforced plastic (FRP), and conversion to non-plastic products (electricity, oil) on a United States economy-wide basis. Integrating system dynamics into this robust plastics model that already incorporates techno-economics, circularity, and environmental impacts will enable identification of key bottlenecks between manufacturers, waste sorters, and reclaimers that currently prevent rapid decarbonization of the plastics economy. System dynamics (SD) explore the evolution of activities and technologies based on changed macro parameters such as plastic demand and supply, market shifts, and cross-sectoral interactions. This project particularly aims to explore the interplay between, waste collection, plastic waste sorting, recycling, and manufacturing, as well as the effect of plastic bale quality and plastic reuse initiatives on the surrounding process stages. This functionality will facilitate combinatory analysis in which a portfolio of end-of-life pathways are assessed simultaneously, with the exact makeup of that portfolio affected by parameters such as technology scales, resource constraints, and waste mitigation efforts. Integrating SD with the 4P framework enables analyzing the effect of increased revenue and reinvestment into improving process efficiencies, sorting and collection quantities. Through that, market effects of increased recycled resin availability can be studied for the plastics systems model for the US. The results will help identify technical or economic bottlenecks that currently limit efforts to decarbonize the U.S. plastics economy.

Human Behavior at Point of Disposal of PLA

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Monica Rodriguez Morris [1], ***Audrey Stanton*** [2], ***Travis Blomberg*** [2], ***Andrea Hicks*** [1]

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Products are often centered in life cycle assessment work. The users and how they behave during the disposal phase are often considered as stylized scenarios and not necessarily informed by empirical data, but by assumptions and system simplifications. The lack of available waste audits and corresponding data of bioplastics disposal makes it difficult to include real-world data, especially for single use products where the cost of tracking or auditing may be onerous compared with the cost of the product.

We have collected data at a campus facility where “compostable” plastic cups, made of polylactic acid (PLA), are offered at some vendor locations. In this work, eight different trials of waste audits were completed throughout the course of 15 months, the most recent trials finalized in December 2022. During the waste audits, the two different waste streams available in the facility were sorted: recycling and landfill garbage. Plastic cups from each stream were identified and sorted to determine the frequency at which the user places the different types of cups in each waste stream. The types of beverage cups included in the study were: polyethylene terephthalate (PETE), polypropylene (PP), polystyrene (PS) and PLA.

“Correct” and “incorrect” disposal varies depending on the material and the location. In our case, and our facility, the “correct” bin for disposing of PLA is the landfill waste bin, whereas the “incorrect” bin for PLA is the recycling waste bin. PLA is not accepted in the materials recovery facility (MRF) that services the facility of our study. From our initial findings, consumers are just as likely to select the correct bin and the incorrect bin for our location in the case of the PLA cups. Based on our data, we hypothesize that the disposal of the compostable cups is random rather than thought-out. Whereas in the case of PETE, there is a higher likelihood of people selecting the “correct” waste stream (recycling) over the “incorrect” (landfill) waste stream. Therefore, there may be thought-out action underlying the decision making of disposing of the PETE cup that is not present during the disposal of the PLA beverage cup. Some possible explanations may be education, background information, familiarity with the product etc., and therefore people favor disposal of the PETE cup in the recycling bin. The cascading effects human behavior has on solid waste management infrastructure and recovered materials can range from insignificant to very significant. The data collected in this study can be used in future LCA studies to model the use and disposal phase of beverage cups to analyze their environmental impacts and the impact human behavior could have on the waste management impacts of these materials.

Willingness-to-pay for Bioplastic Bottles

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Danyi Feng [1], ***Andrea Hicks*** [2]

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According to the Paris Agreement, plastic production alone will consume 15 percent of the carbon budget by 2050. The carbon footprint of plastic must be reduced within 30 years before reaching the carbon budget for 2050, but it is unrealistic to stop using plastic by then. The development of bio-based polymers (bioplastics) is aimed at providing a replacement for petroleum-based plastics as well as a potential solution by retaining the benefits of petrochemical plastics, while simultaneously facilitating a transition towards a circular economy, reducing fossil resource extraction, and potentially reducing the environmental burden resulting from end-of-life disposal. Currently, there is only 1% of the plastic market made up of bio-based plastic. In order to transition away from fossil-based plastics, production and consumption patterns must be transformed and multiple actors will be involved. Developing a wider market for bio-based plastic products needs consumer acceptance and purchase. In terms of consumption choices, consumers have the power to create market pull, demanding more environmentally friendly products and services. As well as the physical characteristics of sustainable alternatives, consumer willingness to purchase these products plays an important role in environmental benefits. Developing a positive attitude toward sustainable products is the key to promoting sustainable consumption, with attitudes toward a product having a high impact on purchase intentions. In this research, the purpose is to understand the potential for consumers to purchase single use plastic bottles made from CO_2 which has been captured and removed from the atmosphere. Consumer preference (e.g., the appearance of the bottles) for CO_2-based bioplastic bottles compared to conventional plastic bottles (made with fossil fuels) was measured and investigated.

Environmental and Human Health Implications of Bioplastic Production Using CO2 as Feedstock

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

***Danyi Feng* [1], *Andrea Hicks* [2]**

1. Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI, 53706, USA, 2. Wisconsin

Currently, plastic products are now an essential part of our daily lives. Conventional plastic is primarily made from non-renewable fossil fuels such as petroleum, coal, and natural gas. Furthermore, petroleum-based plastic causes significant environmental problems, such as high greenhouse gas emissions and a large number of additives from landfill leachate that percolates into the soil, groundwater, and the ocean. The development of bio-based polymers (bioplastics) is aimed at providing a replacement for petroleum-based plastics as well as a potential solution by retaining the benefits of petrochemical plastics, while simultaneously facilitating a transition towards a circular economy, reducing fossil resource extraction, and potentially reducing the environmental burden resulting from end-of-life disposal. In this project, we will integrate inorganic electrocatalysis with organic biosynthesis, with the purpose of coupling each approach's unique advantages, for continuous and direct conversion of CO_2 into high-value bioplastic products in a selective and efficient way. PHB is one of the bioplastics in the PHAs family that are produced by microorganisms with carbon and energy storage and is the only 100% biodegradable polymer in both anaerobic and aerobic conditions. Carbon sources vary for PHB production, including biomass and organic acid. Acetic acid is one of the CO2-based organic acids as feedstock for PHBs without emissions or waste materials for cell growth that can be produced by CCU technologies. The objective of this research is to analyze and understand the cradle-to-gate environmental and human health impacts of PHBs production at each individual step as well as the integrated system via the life cycle assessment (LCA) method based on experimental data. It is hypothesized that the PHBs made of acetic acid will be a more sustainable alternative when compared to biomass carbon sources.

Robust comparative LCA of circular pavement designs using a probabilistic approach

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Zhaoxing Wang [1]***, Zhi Cao*** [1]

1. *University of Antwerp*

As global climate change becomes evident, reducing CO_2 emissions is regarded as one of the most pressing issues for our industry and society. The asphalt pavement industry is also identified as one of the important CO_2 emission sources. Life cycle assessment (LCA) has been widely used to quantify the environmental benefits of designs or practices that can improve the sustainability of asphalt pavements, such as reusing reclaimed asphalt pavements (RAP) in new asphalt mixtures. However, due to the paucity of representative and good-quality data, uncertainties embodied in LCA results are not always reflected, thus unable to ascertain the benefits of sustainable designs or practices.

Against this backdrop, we developed a parametric and probabilistic approach to characterizing key life cycle stages (e.g., raw materials production, asphalt production, transportation, construction, and recycling) and quantifying the uncertainties associated with input parameters and the resulting uncertainties of outputs. In doing so, we leveraged the Monte Carlo method to propagate uncertainties, the discernability analysis to make robust comparisons, and the uncertainty importance analysis to identify influential parameters to the uncertainties of LCA results. We demonstrated the utility of this approach by applying it to 66 cases selected from 1,374 Flemish motorway segments. For each case, we designed 25 scenarios to reflect the variation in RAP content (i.e., 0%, 20%, 40%, 60%, 80%) and thickness (i.e., +0 cm, +2 cm, +4 cm, +6 cm, +8 cm) of the binder layer.

Discernability analysis shows that: (1) If the asphalt containing RAP has the same performance as virgin asphalt, with the increase of RAP content, we are more confident that circular design (RAP content > 0%) has lower CO_2 emissions than the baseline design (i.e., RAP content = 0%); (2) If 2 cm thicker binder layer is needed to ensure the performance of asphalt with RAP, we need to increase RAP content to at least 40% to gain confidence in the sustainability of our circular design; (3) If 4 cm thicker binder layer is required, we have to increase the RAP content to 80% to ensure that circular design has a better environmental performance. In addition, uncertainty importance analysis suggests that transport distance contributes the most to the uncertainties of LCA results, highlighting the importance of improving data quality for transport distance.

Subnational trade flows of nitrogen for the Japanese agriculture-related consumption

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Azusa Oita [1], ***Taku Ishiro*** [2], ***Kentaro Hayashi*** [3]

1. National Agriculture and Food Research Organization (NARO), 2. Yokohama National University, 3. Research Institute for Humanity and Nature

Nitrogen input to agricultural land is essential for agricultural production. Much of the nitrogen input is lost to the environment during cultivation. The nitrogen footprint is an indicator that sums up all the nitrogen loss during the lifecycle of products. A world multi-region input–output approach[1] and a nutrient-extended input–output (NutrIO) approach[2] for the nitrogen footprint showed the need for an in-depth study of food-related sectors. In this study, we used material-flow-based nitrogen input data and a subnational multi-region non-competitive import input–output table[3] for 2011 to examine the producer-consumer relationships between 47 Japanese subnational regions, namely, prefectures.

We considered five nitrogen sources: chemical fertilizers, organic fertilizers, biological fixation, irrigation water, and atmospheric deposition. The nitrogen loss for the cultivation of 95 crop categories was estimated by subtracting "the nitrogen content in products and residues" from the nitrogen inputs, considering burning off the field. The input–output table has 48 sectors for each of the 48 regions (47 prefectures and foreign intermediate and final input), with nine agricultural sectors: rice, "wheat and barley", miscellaneous crop cultivation, dairy cattle farming, beef cattle, hogs, hen eggs, chickens, and miscellaneous livestock. The nitrogen input and loss of importing crops were set as the domestic average for the corresponding sectors (the total sectoral nitrogen input/loss divided by the sectoral gross output).

The total nitrogen input to farmland was estimated at 1050 Gg-N for domestic land and 900 Gg-N for foreign land. Out of the 1950 Gg of the total nitrogen input, 57% was lost during cultivation, and domestic production was responsible for 54% of the nitrogen loss. Hokkaido, the northernmost prefecture with the largest agricultural production value and cultivated land, had the highest nitrogen loss during production. Prefectures with large agriculture, namely, Ibaraki, Iwate, Kumamoto, Chiba, and Aomori, followed. Hokkaido also had the highest agriculture-related nitrogen footprint for its consumption. Prefectures in the populated Great Tokyo region, namely Tokyo, Chiba, and Saitama, and other populated prefectures, Aichi and Fukuoka, followed.

Much farm-level nitrogen loss was embedded in the subnational trade from agricultural to populated prefectures. It was clearer in the rice sector, which had low foreign influence. In contrast, the "wheat and barley" sector was strongly influenced by imports. On a per-capita basis, the agriculture-related nitrogen footprint was an average of 9.9 kg-N/year, ranging from 3.7 kg-N/year for Nara to 28.7 kg-N/year for Hokkaido. Hokkaido has extensive feed crop cultivation, which increases the mass of nitrogen input and loss per million-yen production. Consumption of its own agricultural production increases Hokkaido's agriculture-related nitrogen footprint. Vice versa, Nara has a relatively low dependency on the agricultural production of Hokkaido. Since Japanese livestock-related consumption is highly dependent on foreign countries and Hokkaido, nitrogen input and loss per production values for importing products can be much higher than the average nitrogen input and loss of the average domestic agricultural production. This overall analysis contributes to a better understanding of sustainable nitrogen management along the supply chains.

1. Oita, A. *et al.* (2016). Substantial nitrogen pollution embedded in international trade. *Nature Geoscience*, *9*(2), 111–115.
2. Oita, A. *et al.* (2021). Nutrient-extended input–output (NutrIO) method for the food nitrogen footprint. *Environmental Research Letters*, *16*(11), 115010.

3. Ishiro, T. *et al.* (2020). The Compilation and Analysis of the 2011 Inter-regional Input-output Table for the Agricultural and Livestock Sector [in Japanese]. *Yokohama Journal of Social Sciences*, *25*(2), 39–52.

Estimation of entity level land use and its application in urban sectoral land use footprint: A bottom up model with emerging geospatial data

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Wei Xie [1], ***Huajun Yu*** [1], ***Yang Li*** [2], ***Min Dai*** [1], ***Xinyi Long*** [1], ***Nan Li*** [3], ***Yutao Wang*** [1]

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Land is an essential resource tomaintain the functioning of the socio-economic system. Due to sectoral land data limitations, previous studies were primarily restricted to a coarse sectoral level or focused mainly on the global and national scales. However,fine-scale land use data are required to provide tailored implications for municipal sustainable development. With emerging geographic data and novel methods, including point of interest data, road network data, and natural language processing, a bottom-up model is developed to estimate the entity-level artificial impervious land use. Then, we conducted a case study in Shanghai to investigate the spatial features, footprints, and intensities of sectoral land use. Our results indicated that 42 sectors in Shanghai had diverse spatial patterns. The transportation sector had the highest level of agglomeration among all sectors, and the manufacturing industry's adjacent land patches had higher sectoral heterogeneities than the service sector. The transportation sector had the largest direct and embodied land use footprint. The residential-related sectors had higher land use intensities, while the high value-added service sectors showed lower land use intensities. Our study indicates that this model offers a novel way of extracting entity-level spatial land use information and is applicable for socio-economic metabolism research. Future studies could incorporate remote sensing images and multiple databases to achieve higher resolution.

Charging toward decarbonized electrification: Revisiting Beijing's power system

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Da Huo [1], ***Qian Zhang*** [2], ***Yujie Dong*** [3], ***Chris Kennedy*** [4], ***Chao Zhang*** [3]

1. *University of Toronto,* ***2.*** *Queen's University,* ***3.*** *Tongji University,* ***4.*** *University of Victoria*

Beijing's power system has experienced a significant transition by eliminating coal-fired power generation and increasing the extent of electrification over the past two decades. This study uses a plant-level dataset, pair-wise energy flow, and customized index decomposition analysis to investigate the driving forces behind Beijing's rapid electrification and carbon mitigation effects. We find that electrification-related factors are responsible for 21.8% of carbon emission changes in Beijing between 1995 and 2019. The extent of electrification in Beijing has doubled from 9.5% in 1995 to 19% in 2019, while the carbon intensity of electricity consumption has reduced by 26%. Particularly, the average emission intensity of Beijing's local power generation has dropped from 860 tCO2e/GWh in 2000 to 370 tCO2e/GWh in 2018, which is far below a critical level at which the high penetration of electricity in transportation and housing should be prioritized for decarbonization. Our results confirm that Beijing is in the best position to accelerate electrification to meet its carbon neutrality goals; however, this will increasingly rely on regionally collaborative decarbonization efforts with surrounding regions.

Contributions of key countries, enterprises and refineries to greenhouse gas emissions in global oil refining 2000-2021

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Shijun Ma [1], ***Tianyang Lei*** [2], ***Jing Meng*** [1], ***Xi Liang*** [1], ***Dabo Guan*** [1]

1. *University College London,* ***2.*** *Tsinghua University*

The refining industry is the third-largest source of global greenhouse gas (GHG) emissions from stationary sources, thus, it is at the forefront of the energy transition and net zero pathways. The dynamics of contributors in this sector such as crucial countries, leading enterprises and key emission processes are vital to identifying key GHG emitters and supporting targeted emission reduction, yet they are still poorly understood. Here, we established a global sub-refinery GHG emission dataset in a long time series based on life cycle method. Globally, cumulative GHG emissions from refineries reached approximately 34.1 gigatons (Gt) in the period 2000-2021 with an average annual increasing rate of 0.7%, dominated by the United States, EU27&UK and China. In 2021, the top 20 countries with the largest GHG emissions of oil refining accounted for 83.9% of global emissions from refineries, compared with 79.5% in 2000. Moreover, over the past two decades, 53.9%-57.0% of total GHG emissions came from the top 20 oil refining enterprises with the largest GHG emissions in 12 of these 20 countries. Retiring or installing mitigation technologies in the top 20% of refineries with the largest GHG emissions and refineries with GHG emissions more than 0.1Gt will reduce the level of GHG emissions by 38.0% to 100.0% in these enterprises. Specifically, low-carbon technologies installed on furnaces and boilers as well as steam methane reforming will enable substantial GHG mitigation of more than 54.0% at the refining unit level. Therefore, our results suggest that policies targeting a relatively small number of super-emission contributors could significantly reduce GHG emission from global oil refining.

Lithium-Sulfur Technology Reduces the Environmental Impact of Lithium-Ion Batteries

Monday, 3rd July - 12:00: Critical Raw Materials 1 (short presentations) (B0.25 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Heng Yi Teah [1], ***Qi Zhang*** [1], ***Kotaro Yasui*** [1], ***Suguru Noda*** [1]

1. *Waseda University*

Lithium-sulfur (Li-S) batteries are expected to be the next-generation lithium-ion batteries by 2050. They exhibit useful properties like high theoretical energy density (2,510 $Wh/kg_{Li\text{-}S}$ vs. 500 $Wh/kg_{NCM\text{-}graphite}$) and an opportunity to replace cobalt and other critical materials, in which sulfur is a petrochemical industry byproduct and an abundance nature resource.

This study aimed to investigate the environmental performance of a new carbon nanotubes (CNT)-based Li-S battery architecture. The CNT acts as binders, conductive fillers, and current collectors; therefore, can reduce battery materials and simplify manufacturing processes. We conducted a process-based life cycle assessment (LCA) to identify the anticipated reduction of environmental impacts in contrast to conventional practices.

First, we designed a battery pack for electric vehicles based on our lab-scale coin cell experiment. We applied BatPaC model to estimate the materials requirement for the expected pouch cells. Then, we performed a cradle-to-gate LCA to evaluate the environmental performance of the Li-S battery. We defined the functional unit as 1 kWh Li-S battery normalized from a 100-kWh battery pack. We modelled the global warming potential impact (GWP100, IPCC2013) on openLCA platform supplemented by the background data from Ecoinvent v3.8.

To support the Li-S technology, we examined three scenarios that were critical to improving the environmental hotspots. We examined the effect of self-supporting CNT matrix in reducing the size of aluminum and copper current collectors in S1. We examined the effect of improving anode material efficiency to reduce lithium in S2. Finally, we examined the effect of reducing DME solvent through increasing the concentration of polysulfide solution for positive electrode production in S3.

Our assessment showed that the proposed Li-S cells were associated with 105 kg-CO2e per kWh (capacity) in the benchmark. The contributors in descending order were anode production, cathode production, process energy during cell manufacture (including dry room), current collectors, and others. Considering the technology improvements, S1, S2, and S3 resulted in 18, 5, and 4 kg-CO2e per kWh reduction, respectively. S1 showed that the effect of reduction of current collectors to 1/10 of size was significant although the CNT production was carbon intensive. S2 showed some improvements based on a target N/P ratio but lithium was still a carbon-intensive material. S3 showed that experimenting with less DME solvent for the catholyte was necessary to reduce the impact on cathode.

Another significant finding was the drying process during the cathode production process. Conventional direct drying requires more heat, supplied by electricity or steam, for solvent evaporation, which is an environmental hotspot. Our approach applies an additional filtration step before the evaporation. This enables the reuse of more than 99% of solvent, and more importantly, reduces the remaining solvent, thus lowering the heating energy significantly.

In comparison to a reported Li-S battery, which applied a graphene-oxide sulfur cathode, our proposed Li-S architecture could reduce up to 43% global warming potential, showing a promising alternative. However, there were some limitations in this study. We have calculated energy use of dry room based on cell mass due to lack of reliable data, while the actual electricity use is related to the usage time in the facility. The Li-S battery has a short cycle life (~100 cycle) due to lithium dendrite growth issue at current development; the cycle life was not considered.

Prospective life cycle assessment: the way forward

Monday, 3rd July - 12:14: New IE developments (short presentations) (B0.13 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Rosalie van Zelm [1]***, Mark Huijbregts*** [1]***, Thomas Hennequin*** [2]***, Anne Ottenbros*** [3]***, Emma Zuiderveen*** [2]***, Mitchell van der Hulst*** [1]

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Prospective Life Cycle Assessment (pLCA) has been increasingly used to predict the future environmental impacts of emerging technologies. It allows an emerging technology, still in early development, to be modeled at a future, more-developed phase. Environmental hotspots in the production process can thus be found in an early phase of the industrial design planning. Furthermore, comparison of these emerging technologies to existing, mature technologies becomes more representative, which aids investors and policy makers in decision making. Several frameworks exist to perform pLCA. When applying pLCA to a specific case study a choice can be made for one framework, or a combination of multiple, depending on the case. However, while the frameworks are of help to systematically assess any case, they lack detail on application of specific estimation methods per case study.

The goal of our work is to develop a systematic and case-specific approach for upscaling environmental impacts, which can lead to realistic environmental impact predictions on industrial scale, so we can provide recommendations in an early-development phase.

To further refine existing approaches, we performed a variety of case studies, i.e. for photovoltaics, carbon capture and storage, direct air capture, a chemical synthesis, and chemical recycling of plastic waste. Our starting point was always the 5 steps for upscaling in the framework by van der Hulst et al. (2020), often supplemented with a specific framework focusing on the type of process or technology at hand. Whereas process changes, size scaling, and process synergies are needed to go from lab to industrial scale, industrial learning and external developments are applied from early to mature industrial production. Every step was addressed with a modeling or estimation method that varied depending on the case.

The main results and conclusions we found are that:

- expert consultation is key. While an LCA practitioner can perform the LCA on its own, there is no single method to go from lab to industrial scale that works for every case. The inventory and interpretation will be much stronger with expert input as upscaling is very case-specific. Ideally, this involves process simulations from technology experts.
- the end-of-life phase should not be disregarded. This is currently often done, since time lag between production and end-of-life can be substantial, making the latter very uncertain. However, instead of exclusion, scenario analyses should be performed to include circular options.
- allocation of multifunctional systems should be done based on the avoided-burden approach. This method provides some flexibility over system expansion as the fate of side-products is not always known. Moreover, it should be considered that avoided-burdens could change over time as replaced processes in the future could differ from processes that are replaced now, i.e. the counterfactual might change.
- Publicly available data for research is invaluable. This includes both historical environmental accounting for learning rate calculation, but also accessible prospective databases and background scenarios. These data should ideally be centralized and curated.

In the presentation, our results based on the case studies will be shown and the way forward presented.

Reference:

van der Hulst MK, Huijbregts MAJ, van Loon N, Theelen M, Kootstra L, Bergesen JD, & Hauck M. (2020). A systematic approach to assess the environmental impact of emerging technologies: A case study for the GHG footprint of CIGS solar photovoltaic laminate. Journal of Industrial Ecology, 24(6), 1234-1249. doi:https://doi.org/10.1111/jiec.13027

What are sustainable plastics? A review of interrelated problems and solutions.

Monday, 3rd July - 12:14: Computational methods (short presentations) (B0.17 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Sara Gonella [1], ***Vincent de Gooyert*** [1]

1. Radboud University

There is increasing attention to the sustainability issues related to plastics: greenhouse gases are released during their production and end-of-life management; millions of tonnes of plastics leak every year, causing environmental and health risks; when collected, plastics are often disposed of in landfills or incinerated; most recycled plastics are downcycled into a lower value product.
Conversely, plastics are affordable and versatile, and their use has been widely adopted in various sectors and industries. Plastics even have sustainability credit in some applications. For instance, food packaging is essential to our modern lifestyle and significantly reduces food spoilage. Alternative materials may not be as good at preserving food, may be less safe from a contamination point of view, may be more expensive, and may not necessarily be more sustainable.
The aim of this study is to provide a comprehensive overview of the sustainability problems associated with plastics and the solutions that are currently found in the literature. The study contributes to several discussions by showing how different problems and solutions are interconnected and influence each other, whereas they are usually analysed in isolation. As there is still no common definition of “sustainable plastic”, this study will check what this expression is associated with in the literature, e.g. a specific technology or concept.
The search is based on scientific review and overview articles and grey literature, such as reports from international organisations, NGOs and consultancy firms. The selected documents are coded using an open and axial coding approach. The aggregated variables are linked together by causal links, finally obtaining a qualitative System Dynamics model, following a procedure similar to that proposed by Eker & Zimmermann (2016) and Gürsan & de Gooyert (2021). The model highlights the feedback mechanisms that determine the (un-)sustainability of the system, the impacts that different interventions have on the plastics value chain, and the thematic areas that require further investigation to advance the transition towards sustainability.
Solutions discussed in the literature as potentially enabling a sustainable plastics transition range from bioplastics, recycling technologies, carbon capture and utilisation, banning single-use plastics, behavioural changes, etc. Most research to date has focused on technical solutions to one aspect of the problem; however, technologies do not operate in isolation, but are embedded in a complex socio-economic context. The widespread adoption of each solution would have different impacts and consequences on the plastics industry (new investments of different types and sizes might be required) and on the wider world system (e.g. large-scale production of bioplastics might have an impact on land use).
Alternative solutions could compete with each other for resources, funding and investment. Channelling a large amount of investment into one technology could create a new lock-in situation, which would make it difficult to switch (again) to a different, more sustainable technology, should it become available in a few decades. Taking effective measures against the unsustainability of the plastics system requires large-scale applications, but not all emerging technologies may have the potential to still be sustainable if brought to a large scale. It is therefore necessary to assess the impacts a new socio-technical system could have, to avoid causing undesirable side effects, perhaps even worse than those of the previous system. This study differs from many previous researches in its multidisciplinary and comprehensive approach to the topic of plastics and sustainability.

Factors driving China's carbon emissions after the COVID-19 outbreak

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:21: Flows and emissions (short presentations) (B0.25 KOG)

xinlu sun [1]***, Zhifu Mi*** [1]

1. University College London

The COVID-19 pandemic has swept across the world and exerted a profound impact on China's economic development and carbon emissions by halting economic activities as well as structural changes. Previous studies have a lack of data and therefore focused on quantifying the changes in carbon emissions rather than identifying structural changes in the driving factors of carbon emissions.

The authors of this study use the latest China input-output table and apply structural decomposition analysis to investigate the pattern changes in the driving factors of carbon emissions in China from 2002 to 2020, especially the structural changes in 2020. Carbon emissions are decomposed into five determinants (per capita consumption, population, production structure, consumption patterns, and energy efficiency) and the potential structural changes caused happened after COVID-19 are analyzed.

In the study, the authors show that the most significant change in the driving factors of carbon emission growth in 2020 is production structure, the contribution of which had declined since 2007 but rebounded in 2020. The changes in production structure were because of lower production efficiency and reliance on carbon-intensive inputs. Lower production efficiency indicates that the intermediate input intensity became higher in 2020, meaning that more intermediate input was required to produce the same amount of output. This usually represents less value-added created and lower productivity. The reliance on carbon-intensive inputs was shown by the increased proportion of carbon-intensive inputs in total inputs increased in 2020, for example, the preference for fossil fuels in the transport sector. Due to the halted economic activities in the first half of 2020, the contribution of per capita consumption to emission growth declined.

Therefore, the authors suggest increasing investment in low-carbon industries to avoid future carbon emission trajectories locked in the high-carbon industries and increasing the proportion of consumption in GDP to decrease the carbon intensity of final demand and to achieve a green and robust economic recovery from the pandemic.

Undoing the lock-in of urban sprawl: integrated modelling of materials and GHG emissions of urban transformation for decreasing car dependency

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:21: Mobility (short presentations) (B0.13 KOG)

Laura À. Pérez-Sánchez [1]***, Tomer Fishman*** [2]***, Paul Behrens*** [3]

1. Universitat Autònoma de Barcelona, 2. CML Leiden, 3. Leiden University, CML

The extensive penetration of cars has facilitated suburban sprawl, reinforcing further car dependency through the 20th century. The long lifetimes of suburban infrastructure present barriers to sustainable mobility, which would require a profound transformation in the densification of urban forms to enable the location of residents closer to services and work. Here we analyse the dilemma of prematurely demolishing single-family houses to densify urban forms by assessing the effects on land use, material demand and stocks and GHG emissions. We build an integrated Product Flow Analysis of dwellings and car ownership & use in Sweden by municipality type (2020-2100). The up-front carbon emissions in new construction for densification are only paid off in the long-term by the savings on mobility. These emissions savings are minor in the context of urgent, short-term decarbonisation and vary more with the level of electrification of transport. The denser final built environments may have further social benefits and free half the current residential land use.

A theoretical method to evaluate and compare changes in energy consumption reduction of vehicles

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Gabriel Magnaval [1], ***Anne-Marie Boulay*** [1], ***Guillaume Majeau-Bettez*** [1]

***1.** CIRAIG, Polytechnique Montréal*

Faced with large emissions caused by vehicles, the road transportation sector is looking for solutions to reduce its impact on the environment, and namely energy consumption of vehicles. Three main categories of changes are possible to reduce vehicles' consumption : technological innovations; policy regulations; and evolutions in drivers' behavior. Are these changes all beneficial from a systemic point of view that considers the entire life cycle of the vehicle? Which changes should be prioritized?
Literature shows that there is no method for transparently and consistently evaluating the potential fuel reduction associated with all these different types of changes. To date, studies focus on lightweighting (Koffler & Rodhe-Brandenburger, 2010 ; Kim & Wallington, 2013 ; Del Pero et al. , 2017) and transparency of the models – namely in powertrain efficiency assessment– is a challenge.

Therefore a methodology has been developed, based on a theoretical approach of vehicles' energy consumption. First the instantaneous power needed by the vehicle is expressed. This power is calculated by summing external forces that the vehicle must overcome and energy losses during the power transmission from tank to wheels. The instantaneous power depends on the vehicle and its dynamics, the engine, the gearbox and the battery. Second, instantaneous power is integrated over time to obtain the total energy consumption. Dynamic parameters are expressed as a function of the path and the driver's behavior. Finally, the parametrized equation can be derived to highlight the influence of any of the parameters on the energy consumption. For example, a practitioner could derive energy consumption as a function of vehicle mass to get a specific expression for the potential fuel reduction of lightweighting.
This methodology builds on existing literature which have developed similar models (Sovran et al., 2003 ; Sacchi et al., 2022), but proposes three innovative improvements: 1) In the calculation of the external forces, road grade is now considered. A statistical distribution of the inclination of the roads in the studied region allows to describe the slope encountered by the vehicle; 2) Losses in powertrain are not averaged, as is the case in most models, but are approximated from efficiency maps and specific literature (Ross et al., 1997 ; Murakana et al., 1989); and 3) The path followed is not modeled by driving cycles, which neglects, among others, driver's behavior. Instead, an approach close to the VECTO method of the European Commission is favored. The roads are characterized by a target path, and a real speed is calculated according to parameters characterizing the driver's behavior.
These improvements ensure more extensivity and consistency to the methodology. By introducing new parameters, many technological innovations can be assessed – checking for potential burden shifts – and compare with social evolutions . Assessment could be done for both thermal and electric vehicle. Moreover, the parametrization of potential fuel reduction helps optimizing data collection. LCA practitioners can easily identify the most influential parameters that should be considered in priority.
Finally, the methodology is a cornerstone for prospective LCA. As the model relies on physical relationships, resulting equations are independent of temporal context. Prospective LCA can then be performed using these equations by quantifying key parameters introduced and their evolution over time. Decision makers will then be able to evaluate prospective impacts of the most promising changes and optimize the evolution of automotive industry.

Financing high-cost measures for deep emission cuts in the basic material industry

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Anna Hörbe Emanuelsson [1], ***Johan Rootzén*** [2], ***Filip Johnsson*** [1]

1. Chalmers University of Technology, 2. IVL Swedish Environmental Research Institute

This work contributes to new ways of financing investments required to accelerate the transition towards net-zero emission practices in the basic materials industries, such as cement, steel, and pulp, which are major emitters of both fossil and biogenic carbon dioxide (CO_2) emissions.

Even though there are signs of increased ambitions in the climate policies targeting the industry sector there is a risk that current practices and policies will only deliver incremental reductions in carbon emissions on a timeline that is far too slow to meet the deep emissions cuts required over the next decades to be in line with the Paris Agreement. The necessary transformative abatement options such as CCS and hydrogen-based steel making require large investments, which imply a high financial risk and are therefore unlikely to be initiated under the current climate policy regime. As means to accelerate the transition of the basic materials industry, to engage non-state actors in the process and to formalize cross-sectorial collaboration, we investigate how the costs and risks associated with such high-cost measures can be distributed and shared along product value chains through various financing schemes. Increasing consumer preferences for climate neutral products and services and an increasing pressure on firms to make explicit and take responsibility not only for the emissions that are under their direct control (Scope 1) but also for upstream and down-stream emissions (Scope 2 and 3) opens up for collaboration and risk sharing among actors involved in the value chain for carbon intensive basic materials.

This work takes as point of departure two case studies representing two different basic material industries, the cement industry and the pulp industry, with different characteristics in terms of raw materials, market structure and end-uses. By assessing two very different industries we hope to capture differences in possibilities and challenges related with varying types of value chains and end-products. The cement industry is a nationally traded commodity which is commonly used in large and complex construction and infrastructure projects with many actors involved, while pulp is an internationally traded material and typically used in various high-volume consumer goods.

The aim with this work is to illustrate how costs and risks related to the financing of high-cost abatement measures in the basic material industries can be distributed along the value chain. Different ways of financing are explored such as transition funds where actors along the value chain establishes collective action and pays a fee that goes into the fund, and third-party actor involvement which collects a premium value of end-products sold with additional embedded costs due to investment in low-carbon technologies. The revenues from these two financing schemes can then be used for investments in high-cost mitigation technologies. These financing mechanisms will be compared to policy instruments such as Carbon Contracts for Difference (CCfD) among other. By distributing the costs and risks associated with the investment along the value chain, investments in costly abatement technologies could be facilitated while minimizing the risk of individual companies as well as for governments and taxpayers.

Keywords: Sustainable financing, value-chains, collective action, cement, pulp

Environmental impacts and potential improvements of rare earth mining

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Maarten Koese [1] ***, René Kleijn*** [1]
1. *Leiden University, CML*

Demand for Rare Earth Elements (REEs) has grown drastically the past few decades and is expected to increase even more due to the energy transition. One of the most important applications of REEs are neodymium-iron-boron (NdFeB) magnets, used in electronics, electric vehicles and wind turbines. To keep up with this growing demand, supply must increase. One way to achieve this is by increasing recycling rates, but additional supply of virgin materials will also be necessary to fulfill the demand. Currently, virgin REE supply is mainly controlled by China, accounting for around 60% of primary and approximately 95% of refined supply. The European Union (EU) is very dependent on China for its REEs, a vulnerable position considering the strategic importance of REE applications. This means the EU will also be looking at diversification of virgin REE sources.

In the past decade, exploration efforts have increased and as a consequence several new REE mines will be opened in the near future. Even though supply from these mines will contribute to a more diverse supply chain and thus increase resilience, it is not clear whether the sourcing from these alternative sources is also more environmentally sustainable. The mining of REEs is associated with detrimental environmental impacts, such as acidification of soil and groundwater and high energy requirements leading to CO2 emissions. Most studies about the environmental impacts of REE mining consider existing mines, e.g. Bayan Obo in China, or Mt. Weld in Australia, but not newly operational sites.

In this paper, the environmental impacts of a primary REE mine – located outside of China and soon to be operational – will be assessed through Life Cycle Assessment (LCA). The analysis will be based on primary data supplied by the mining company, which will be modelled and analyzed through Activity Browser. Furthermore, different options to increase sustainability for the mining will be explored, such as, but not limited to, using fully renewable energy and electricity-powered machinery, the use of irrigation systems to prevent spreading of radioactive dust, and dealing with tailings adequately to prevent accidental releases. These will also be modelled and their environmental impacts will be assessed. This paper will thus provide a comparative analysis in terms of environmental impacts of the common primary RE mining process, and doing it in the most sustainable and advanced way possible with current technology. A RE mine in Africa, which will be operational from 2024 onwards, will serve as a case study for this.

This research will provide insight into the sustainability of future virgin REE supply and explore how much room for improvement there is. It may serve as a basis to limit the environmental impacts of the assessed RE mine, but also for other RE mines across the globe. This is especially relevant due to the increasing need for REEs and the amount of mines that will be opened to meet this demand. The insights from this study enable policymakers and technology manufacturers to make well-informed decisions about REE sourcing.

Bottom-up characterization of the urban metabolism of reusing electric vehicle batteries

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Tuesday, 4th July - 12:07: Urban IE (short presentations) (B0.17 KOG)

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Two objectives converge at the reuse of electric vehicle batteries for stationary energy storage: renewable energy intermittence management and reduction in environmental impacts for battery fabrication. The study of the environmental benefits and impacts of reusing EV batteries has been focused on two main aspects by two main methodologies. First, single battery scale Life Cycle case studies proposing the avoidance of a new battery have focused on CO saving and, second, regional and global scale studies employing Material Flow Analysis to quantify the mineral extraction required under different scenarios. In this study, we aimed at advancing in the assessment of greenhouse gas emissions and mineral savings of reusing EV batteries by inferring their potential incorporation and targeted use in a local scale study. Supported by a series of four household surveys, of above 1,000 respondents each, on dwelling typology and family time use, we studied the urban metabolism of a medium sized city in the metropolitan area of Barcelona, with broad household inequality, diversity of dwelling typologies, and abundance of industrial and service facilities. The study of the current status shows that both the dwelling typology and the inhabitants typology are determining factors in the household's tools for adaptation to increasing energy prices and increasing prices volatility, presenting high contrast in technological solutions versus social adaptation. From the characterization of current household patterns, we provided EV batteries' end-of-life and reuse scenarios, proposing the metabolic patterns required and derived of such scenarios in the urban context. In line with previous studies, we found that the GHG emissions savings derived from the use of batteries for household purposes could turn negative depending on the household typology and the status of the electricity market. Additionally, the increase in battery reuse flows will be abrupt and may not avoid the need for upcoming intense mineral extraction if EV sales targets are met. Lastly, from scenarios based on the current policy and administrative patterns, we found an increase in inequality for the access of energy. These results suggest a need to revise current policies to align with the claimed purposes of battery reutilization.

Exploring the impact of a circular economy: A model-based analysis of steel and cement demand for buildings

Monday, 3rd July - 12:35: Circular economy (short presentations) (A1.44 KOG)

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

Meta Thurid Lotz [1], ***Andrea Herbst*** [1]

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Growing consumption levels and consequently increasing demands for goods and associated materials contrast the efforts currently undertaken to reduce greenhouse gas emission to mitigate climate change. A main contributor to the demand for the energy- and emission-intensive materials steel and cement is the building sector, which is currently responsible for about one quarter of steel demand and more than three quarters of cement demand in the European Union. On the one hand, this consumption could increase in future due to a rising demand for living spaces and service-related buildings. On the other hand, circular economy strategies, such as design for reuse, closed-loop recycling or material substitution could reduce this demand and contribute to achieving climate-neutrality. Accordingly, quantifying the impact of such measures is essential, in order to address and exploit the potentials systematically. We contribute to this by extending an existing material flow model with three exemplary circular economy actions: (1) Extending building lifetime through repair and renovation; (2) Using wood as main construction material instead of (reinforced) concrete; (3) Reusing prefabricated building elements. The modelling scope includes residential, commercial and public buildings in the European Union and United Kingdom. It differentiates building archetypes for three regions, five age cohorts and six building types. We modeled the stock, in- and outflows of steel and cement according to a predefined building stock development and consider circularity through three approaches: (1) Adapting the building stock development; (2) Adapting the building archetypes; (3) Introducing new flows into the model. We conducted a literature review to systematically identify potentials, limitations, preconditions and interactions of the circular economy actions and parameterized them to reflect the potential impact bandwidth compared to a reference scenario. The results show steel and cement reduction potentials of the individual circular economy actions. In particular, extending the service life of buildings and changing the main construction material can significantly reduce the prospective demand for steel and cement, but require adaptions of user and constructor behavior. In contrast, the reuse of building elements has a lower potential impact on the prospective material demand. However, the reduction potentials are characterized by uncertainty for various reasons, such as low technology readiness levels, necessary changes in the regulatory framework or behavioral trends and interaction with other transformation strategies. The presented approach enables the systematic comparison of such aspects for scenario analyses. This will be extended to further circular economy actions and validated through expert interviews. Consequently, this lays the foundation for comprehensive and consistent circular economy scenarios and the improved consideration in energy system analysis.

Material Flow Analysis of the Portuguese plastic management

Monday, 3rd July - 13:00: Poster session 2 (Pieterskerk)

João Serra [1], ***Paula Quinteiro*** [1], ***Ana Cláudia Dias*** [1]

1. *University of Aveiro*

Plastic is one of the most used widely materials and is one of the most widespread and persistent pollutants on the planet, constituting a serious problem for society. To promote a circular economy of plastics, it is important to understand its current life cycle, by quantifying the different plastic material flows from the production stage until their end of life (EoL). In this sense, it becomes possible to identify opportunities to reduce the environmental pressure on the consumption of resources for plastic production. This can be achieved by conducting a Material Flow Analysis (MFA), which is a widely used tool to support policymakers to understand material flows along all product life cycle stages and provide suggestions for improving product sustainability. There has been a growth of this type of analysis in several countries, mainly to evaluate plastic waste management. However, for Portugal, there are no published studies on this theme.

In this context, this study proposes a framework to support the development of an MFA to determine the main flows of plastics used in Portugal, including the stages of production, consumption, and EoL (e.g. recycling, incineration with energy recovery, landfill, reuse, mismanaged and leak to ocean and waterways). The framework proposed consists of 4 steps: 1) identification of the relevant data categories at each stage of the life cycle; 2) identification of reliable data sources that have information related to the categories of data considered. Such sources could include industrial reports, direct contact with stakeholders, statistical databases, governmental data, and scientific literature; 3) collection of data from the different sources identified; 4) validation of the quality of the data acquired, considering factors such as credibility of the data source, methodology used for data collection, and the relevance of the data for the specific analysis.

In conclusion, the proposed framework is a starting point for the development of an MFA for plastic used in Portugal, as well as for the identification of gaps and improvements related to the acquisition and quality of data.

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