RISING TO GLOBAL CHALLENGES

25 Years of Industrial Ecology

International Society
for Industrial Ecology

This booklet is compiled by the International Society for Industrial Ecology (ISIE) to provide an overview of current teaching, research, and achievements in Industrial Ecology (IE). The Society aims to promote IE by providing updated information to academic institutions as well as the general public. This booklet is available in print and electronic media at *http://www.is4ie.org*.

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CONTENTS

INTRODUCTION TO INDUSTRIAL ECOLOGY

Industrial Ecology

Industrial Ecology (IE) is a growing discipline at the forefront of efforts to understand and act upon our sustainability challenges. This document celebrates the first twenty-five years of mainstream IE, the accomplishments of the International Society for Industrial Ecology (ISIE), and its journal. It describes how through excellent teaching programs, and industrial research collaboration, IE has emerged as an important discipline for addressing global environmental issues.

A variety of definitions of industrial ecology have been advanced including that of Robert White, president of the U.S. National Academy of Engineering (White 1994):

"Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources."

The name industrial ecology reflects significant content of the field. Industrial ecology is "industrial" as it views firms as agents for environmental improvement because they possess the technological expertise that is critical to the successful execution of environmentally informed design of products and processes. Industrial ecology is "ecological" in at least two senses. Industrial ecology looks at non-human "natural" ecosystems as potential models for industrial activity. This is what some researchers have dubbed the "biological analogy" (Graedel 1996). Many biological ecosystems are especially effective at recycling resources and thus are held out as exemplars for efficient cycling of materials and energy in industry and society. Industrial ecology also borrows biological concepts related to the idea of metabolism. Second, industrial ecology places human technological activity industry in the widest sense in the context of the larger ecosystems that support it, examining the sources of resources used in society and the sinks that may act to absorb or detoxify wastes. This latter sense of "ecological" links industrial ecology to questions of carrying capacity and ecological resilience. The field has a strong anchor in engineering, but includes substantial elements of environmental science, environmental and ecological economics, and management.

...IE has emerged as an important discipline for addressing global environmental issues.

History

Industrial ecologists typically date the beginning of the field to the 1989 article in *Scientific American* by Frosch and Gallopoulos which advanced the biological analogy and argued for a systems approach to environmental analysis, management, and policy. Yet, the intellectual antecedents include an important article in the *American Economic Review* (Ayres and Kneese 1969) which outlined approaches to integrating physical limits – specifically material balances – into economic analysis as well as research including Belgian and Japanese scholarship dating back to the 1970s along with elements of sociology (Erkman 2004; Fischer-Kowalski 1998; Fischer-Kowalski and Hüttler 1998). The field incorporates research from several developing literatures including life cycle assessment (LCA), cleaner production, industrial metabolism and corporate social responsibility. A 1992 National Academy of Science Colloquium brought together scholars and led to an important set of papers outlining the key elements and research goals of the field. Recognition of an industrial district in Kalundborg, Denmark where facilities share resources and exchange by-products led to a body of research on "industrial symbiosis" providing an exemplar for the biological analogy (Chertow 2000). In institutional terms, the U.S. National Academy of Engineering and members of AT&T Bell Labs through the AT&T Foundation played key roles supporting the coalescence of the field.

The field has a strong anchor in engineering, but includes substantial elements of environmental science, environmental and ecological economics, and management.

The appointment of Thomas Graedel at Yale in 1997 established, as best as can be ascertained, the first professor of industrial ecology. The *Journal of Industrial Ecology* was founded in the same year and

U.S. DEPARTMENT OF LABOR DEFINITION OF INDUSTRIAL ECOLOGISTS

The U.S. Department of Labor's O*NET (Occupational Information Network) program describes the 'New & Emerging' occupation of Industrial Ecologists and their work (NCOD 2015):

> *"Apply principles and processes of natural ecosystems to develop models for efficient industrial systems. Use knowledge from the physical and social sciences to maximize effective use of natural resources in the production and use of goods and services. Examine societal issues and their relationship with both technical systems and the environment."*

The tasks undertaken by industrial ecologists include:

- Analyze changes designed to improve the environmental performance of complex systems to avoid unintended negative consequences.
- Apply new or existing research about natural ecosystems to understand economic and industrial systems in the context of the environment.
- Carry out environmental assessments in accordance with applicable standards, regulations, or laws.
- Conduct analyses to determine the maximum amount of work that can be accomplished for a given amount of energy in a system, such as industrial production systems and waste treatment systems.
- Develop alternative energy investment scenarios to compare economic and environmental costs and benefits.
- Evaluate the effectiveness of industrial ecology programs using statistical analysis and applications.
- Examine local, regional or global use and flow of materials or energy in industrial production processes.
- Examine societal issues and their relationship with both technical systems and the environment.
- Identify or compare the component parts or relationships between the parts of industrial, social, and natural systems.
- Identify or develop strategies or methods to minimize the environmental impact of industrial production processes.

The most recently updated information, including additional details about the occupation of Industrial Ecologists, is currently available online at *http://www.onetonline.org/link/details/19-2041.03*.

National Center for O*NET Development. 19-2041.03. O*NET OnLine. Retrieved March 11, 2015, from *http://www.onetonline.org/link/summary/19-2041.03*.

the first Gordon Research Conference on Industrial Ecology was held the following year. In 2001 the International Society for Industrial Ecology was established and the first international conference was held at Leiden University in the Netherlands.

Elements of Industrial Ecology

The hallmarks of industrial ecology are a cluster of concepts and tools:

Life cycle assessment

Product-oriented environmental management and policy

Material and energy flow analysis (MEFA, also called socio-economic metabolism)

Industrial symbiosis

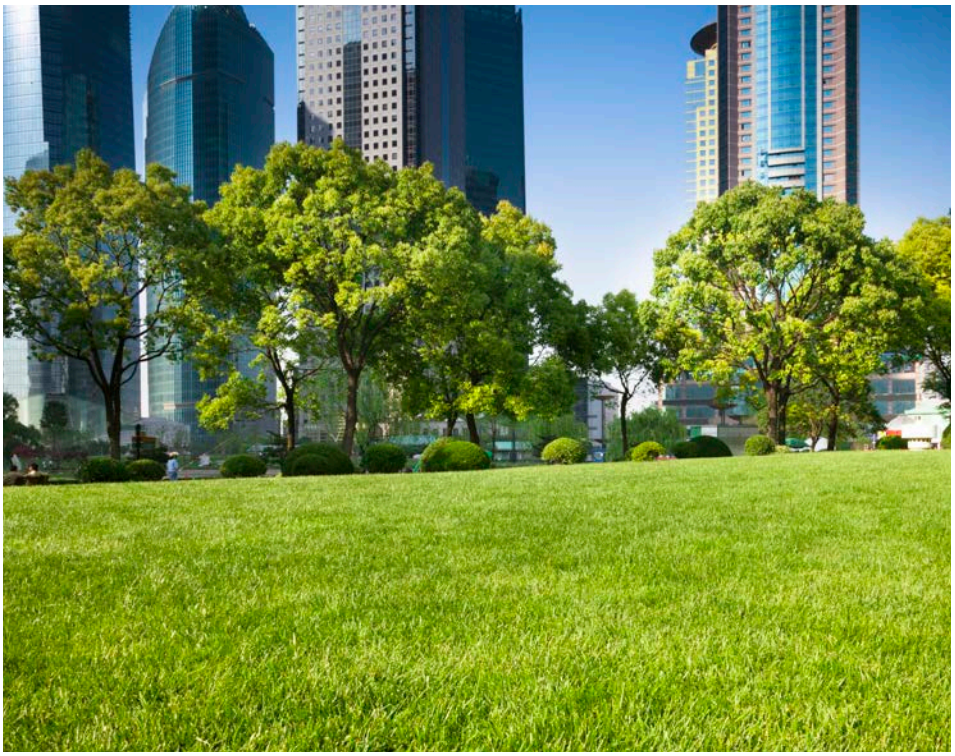
Eco-efficiency

Dematerialization and decarbonization

Uniting these elements are attention to the flow of materials and energy at multiple scales – unit processes, products, supply chains and product life cycles, facilities and groups of facilities, firms, cities, regions, and the globe. Through approaches such as life cycle assessment, design and management, and rigorous materials accounting, industrial ecology also pursues its comprehensive systems perspective (Lifset and Graedel 2002).

In the early days of industrial ecology, investigation of the soundness and utility of the biological analogy and efforts at eco-design were prominent. In the past decade, input-output analysis (especially multi-regional IOA), studies of resource criticality, integration of social science and operations research, agent-based/complexity modeling, urban metabolism and long-term socio-ecological research have become central to the field.

ACCOMPLISHMENTS OF INDUSTRIAL ECOLOGY



The influence of industrial ecology is significant and growing, and the analytical tools that are central to the field, such as life cycle assessment (LCA) and material flow analysis (MFA), are increasingly used in other disciplines. Both LCA and MFA are used in the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report to examine the embodied greenhouse gas (GHG) emissions from buildings, transportation, and other sectors. Additionally, industrial ecology specialists comprise the core of the United Nations Environment Programme's (UNEP) International Resource Panel. They have authored five of the Panel's seven reports since 2011.

From a policy perspective, Japan, China, and the European Union all have laws or polices related to such topics as material flow analysis reporting, the circular economy, and a sound material society. The European waste management policy has been highly influenced by IE concepts and practices, notably Extended Producer Responsibility. In Portugal, IE has been used to develop the national waste management plan; and IE is now explicitly incorporated within the Constitution of the Canton and Republic of Geneva. The now standard approaches to material flow accounting used in the EUROSTAT Environmental Accounts and by the Organization for Economic Cooperation and Development (OECD) were largely developed by industrial ecologists.

Advances in methodologies for assessing environmental impacts are also among the accomplishments of the field. Industrial Ecologists have written the guides and handbooks behind the ISO standards for Life Cycle Assessment (Guinée et al., 2002); and they are leading the development of improved methods of Life Cycle Sustainability Assessment (Guinée et al., 2011; Heijungs et al., 2010; Hu et al., 2013). They have also furthered the development of environmentally extended input-output models assessing economy-wide environmental impacts (Huppes et al., 2006; Tukker et al., 2013). In another case, industrial ecologists have helped to evolve the popular method of ecological footprint into more rigorous measures of carbon, water, nitrogen and other types of footprint (Hoekstra and Wiedmann, 2014).

Recent publications in top scientific journals such as *Nature, Science* and the *Proceedings of the National Academy of Sciences* signal the coming of age of the field. Examples include work on the scarcity of metals (Reck and Graedel, 2012) and the impacts of global trade on biodiversity loss (Lenzen et al., 2012; Hertwich, 2012). Scholars of IE have been measuring China's circular economy (Geng et al., 2013), assessing its sustainability targets (Geng, 2011) and analyzing its urban policies (Bai, 2014). Research by industrial ecologist is revealing the widespread impacts of humans on the natural environment, such as the human appropriation of net primary production (Krausmann et al., 2013) and the long legacy of species extinction in Europe (Dullinger et al., 2013). IE is contributing on a wide range of topics, from planetary boundaries (Erb et al., 2012) and the weight of nations (Wiedmann et al., 2013), to forest carbon sinks (Erb et al., 2013), low carbon urban infrastructure (Kennedy et al., 2014), and the behavior of nano-particles in thermal waste treatment (Walser et al., 2012). These examples are just the tip of the iceberg of a large and growing body of work by ISIE members.

THE SOCIETY PRIZE

The Society Prize is awarded for outstanding contributions to the field of industrial ecology. It is the ISIE's highest recognition of professional achievement. The past recipients are:

2003 ROBERT U. AYRES

Robert Ayres was recognized for constructing the basic ideas that have comprised industrial ecology since the late 1960s. Under several different descriptions and model names, he pointed to the importance of examining material and later energy flows in a systematic framework both in order to truly understand them and to develop rational polices for managing these resources. The work was groundbreaking in that it introduced thermodynamics, in this case the First law, to studies of waste and pollution. Ayres developed the notion of material flow based analysis of industrial systems and produced some of the very first comprehensive data on life cycles of common industrial processes and substances. This work predated the emergence of LCA as a key method in the field. In the late 1970s, Ayres again anticipated another mainstream development, that of material flow accounting (MFA) in a book suggesting its use as a policy tool.

His metaphor of industrial metabolism predates the industrial ecosystem metaphor that is now a central image underpinning the field. Before the notions of material and substance flow analysis became popular as research areas in recent years, Ayres had assembled the largest database and body of analytical work examining the flows of key substances like copper and chlorine. His *magnus opus* on chlorine flows was the subject of several important articles in the *Journal of Industrial Ecology* and helped it to gain the intellectual credibility it now possesses.

But he has contributed much more than material and energy systems frameworks. His work on thermodynamic implications for industrial ecology (and economics) is only now beginning to be seen in its fullest import. Ayres was one of the earliest scientists to bring Second Law notions into industrial ecology and to our sister field of ecological economics as well. His early works stressing the importance of exergy as the proper measure to use in studying energy use are cited widely in current research papers showing up in the *Journal of Industrial Ecology* and other high quality journals.

2005 ROBERT FROSCH

Distinguished Harvard University researcher, Robert A. Frosch, was credited with coining the term "industrial ecology", and is one of the founders of the field. Industrial ecologists typically date the beginning of the field to the 1989 article in *Scientific American* by Frosch and Gallopoulos, which advanced the biological analogy and argued for a systems approach to environmental analysis, management, and policy. Robert Frosch is a theoretical physicist by education. He conducted research in ocean acoustics at Columbia and later served as Director for Nuclear Test Detection, and Deputy Director of the Advanced Research Projects Agency in the Department of Defense, Assistant Secretary of the Navy for Research and Development, Assistant Executive Director of the United Nations Environment

Programme, Associate Director for Applied Oceanography of the Woods Hole Oceanographic Institution, Administrator of NASA, President of the American Association of Engineering Societies, and Vice President of General Motors Corporation, before joining the Kennedy School of Government at Harvard University. He is a member of the National Academy of Engineering, the American Academy of Arts and Sciences, a Foreign Member of the UK Royal Academy of Engineering, and a fellow or member of a number of professional societies.

2007 THOMAS GRAEDEL

Thomas Graedel has been among the most significant researchers in industrial ecology, performing important research in streamlined life cycle assessment, design for the environment, and materials flow analysis. He has published prolifically with more than 300 overall publications and more than 70 in the general area of materials flow analysis alone. Aside from research, he has made other important contributions, notably the textbook *Industrial Ecology* that he co-authored with Brad Allenby. Thomas Graedel is widely recognized for his leadership in building a community of industrial ecologists. He contributed to the founding of the *Journal of Industrial Ecology* and served with distinction as the first of President of the ISIE.

2009 JOHN EHRENFELD

Dr. Ehrenfeld served as Executive Director of the International Society for Industrial Ecology from 2001 until 2008, after retiring as the Director of the MIT Program on Technology, Business, and Environment. John Ehrenfeld made many contributions to Industrial Ecology through his research and writing, including a classic paper on industrial symbiosis at Kalundborg, Denmark, as well as work on complex systems and sustainability. In October 1999, the World Resources Institute honored him with a lifetime achievement award for his academic accomplishments in the field of business and environment. He received the Founders Award for Distinguished Service from the Academy of Management's Organization and Natural Environment Division in August 2000. John Ehrenfeld was a Visiting Professor at the Technical University of Lisbon as a Fulbright Distinguished Scholar and at the Technical University of Delft. He is an editor of the *Journal of Industrial Ecology.* He holds a B.S. and Sc.D. in Chemical Engineering from MIT, and is author or co-author of over 200 papers, books, reports, and other publications.

2011 GJALT HUPPES

Dr. Gjalt Huppes is the former head of the Department of Industrial Ecology, CML, at Leiden University. He was awarded the Society Prize for his achievements in the field of Industrial Ecology, in particular his pioneering work in life cycle assessment, substance flow analysis and environmentally extended Input-Output analysis. Through this and his leadership in organizing international conferences, chairing key UNEP committees and heading the Industrial Ecology department at CML for over two decades, he has had a tremendous impact in the field.

2013 YUICHI MORIGUCHI

Yuichi Moriguchi is the former Director of the Research Center for Material Cycles and Waste Management at the National Institute for Environmental Studies in Japan, and is currently Professor of Urban Engineering at the University of Tokyo. His major areas of research have been material flow analysis (MFA), including its integration with life cycle assessment, input-output analysis, with applications for material recycling and measures of sustainable consumption and production. In 1997 and 2000, Yuichi Moriguchi published joint U.S.-Europe-Japan international research reports on MFA, which contributed to the standard approaches now used by the Organization for Economic Cooperation and Development, among others. Dr Moriguchi is a member of a technical advisory group for Japan's Environment Ministry on sound material cycles in society, GHG emissions inventory, GHG reduction policy, life cycle assessment and environmental indicators, and an editorial committee member for the Japan Society of Material Cycles and Waste Management. He earned a Ph.D. in Sanitary and Environmental Engineering from Kyoto University in Japan.

THE INTERNATIONAL SOCIETY FOR INDUSTRIAL ECOLOGY

The International Society for Industrial Ecology is an interdisciplinary forum of natural and social scientists, engineers, policymakers and practitioners inspired by the industrial ecological metaphor and by concerns for sustainability. Founded in 2001, its mission is:

- To advance the development of systems based analysis methods, tools and solutions in pursuit of sustainable technologies, product and service systems, consumption and economies; and
- To promote the use of industrial ecology in research, education, industrial practices, policy, and community development in order to transform society and achieve a more sustainable economy.

Members of the ISIE are able to join subject specific sections as part of their membership. Sections provide a focused community within the ISIE through which ideas are exchanged and collaborations are formed. There are currently six subject sections that over half of the ISIE members participate in.

Life Cycle Sustainability Assessment (LCSA)

Practitioners in the LCSA section are applying current methods of life cycle assessment (LCA) to determine impacts of various products and processes; and developing new methods that apply life cycle perspectives towards sustainability assessment. This section is intended for those working in the field of LCA and LCSA and also for those interested in bringing other life cycle based tools together and linking them to appropriate questions and applications.

The LCSA section offers a platform for discussing methodology proposals and case studies addressing the broadening and deepening of LCA into LCSA. Topics addressed by the section include: improvement and alignment of life cycle methodologies; linkage with developments in Eco-Efficiency and Eco-Innovation; using LCSA for informing and guiding the overall sustainable development of society; applications at different levels from products, to companies, sectors and societies; and use of life cycle based approaches in modeling future scenarios or back-casting.

Eco-Industrial Development/Industrial Symbiosis (EIDC)

Industrial symbiosis provides competitive advantage for companies through the physical exchange of materials, water, energy and by-products. This collaborative approach adds value, reduces costs and improves the environment.

The EIDC is a not for profit corporation with offices in Minneapolis, Minnesota and is a loose affiliation of public and private sector interests focused upon eco-industrial development or applied industrial symbiosis. Having formed in 2003, this group of North American practitioners voted in June 2006 to formally affiliate with ISIE. It is now an international collective of experts in industrial symbiosis.

Socio-Economic Metabolism (SEM)

ISIE's SEM Section is the largest global network of researchers employing material flow analysis as a tool for environmental sustainability assessment. The purpose of this Section is to develop material flow analysis internationally in academia and to promote its application in policy and businesses. This includes establishing and maintaining cooperation with international organizations, companies, and government organizations.

Sustainable Urban Systems (SUS)

The Sustainable Urban Systems Section is concerned with applying methods of industrial ecology towards the sustainable development of cities, their supporting hinterlands, and the networked infrastructure that connects them. This is an applied, cross-cutting section in which various IE methods, such as LCA, MFA, EIO, complex systems theory and thermodynamics, are applied at the urban scale. Issues addressed include (but are not limited to): developing urban infrastructure for low carbon cities; urban waste management and material recycling; urban transportation; green buildings; sustainable water and nutrient management; urban energy systems; resilient cities; adapting cities to climate change, and provision of infrastructure for the urban poor. Practical solutions to these issues are informed through study of urban ecology, urban metabolism and the dynamics of city growth. Membership of the section is broad ranging, including: urban planners, architects, geographers, engineers, economists, scientists, and others.

Organizing Sustainable Consumption and Production (OSCP)

This OSCP Section explores the challenge of achieving sustainability for product chains. The globalized economy has led to much outsourcing of production, and product life cycles consequently sprawl across the globe. This poses particular challenges for their sustainability management and governance; no single actor has overview, much less control, over an entire production and consumption system, yet changes need to be considered in the context of the entire system in order to reduce environmental impacts. Although LCA can provide comprehensive environmental descriptions for products, the capacity to act upon such information is not automatic – it requires actors that communicate, collaborate, coordinate, etc., their environmental demands, tasks, actions, etc., in these systems. The improved understanding of the issues for environmental organization of product chains is therefore at the heart of the activities of this section.

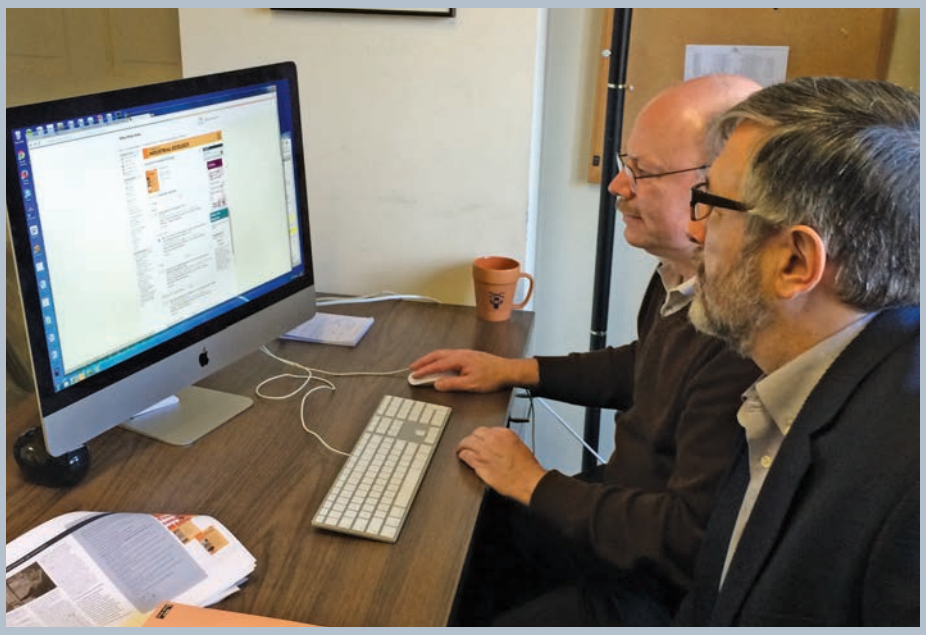
The OSCP Section provides a platform for systematic and interdisciplinary treatment of the management issues of product chains. Its discussions draw upon contributions from supply chain management, life cycle management, environmental management and strategy, product design and service systems, environmental sociology and governance, among others. The development of methodologies that combine environmental studies with study of organization and management is of special interest for the Section.

Environmental Extended Input Output (EEIO)

The purpose of this Section is to develop environmentally extended input output analysis internationally in academia and to promote its application in policy and businesses. This includes establishing and maintaining cooperation with international organizations, companies, and government organizations, including the International Input Output Association.

More specific activities of the Section include: developing best practices in EEIO methodology; providing a platform for exchange of EEIO data in a common format, or mutual support between members in data development; providing a platform for exchange of operational procedures and scripts; engaging with National Statistical Offices and international bodies to improve official data and methodologies used in EEIO; and promoting applications of EEIO in political and corporate decision making.

THE *JOURNAL OF INDUSTRIAL ECOLOGY*: OVERVIEW AND



The *Journal of Industrial Ecology (JIE)* is a peer-reviewed, international bimonthly owned by Yale University and published by Wiley-Blackwell. The *JIE* is the official journal of the International Society for Industrial Ecology.

In its 18th year in 2014, the *Journal* has been described by the prestigious journal *Nature* as:

"timely…[bringing a] global perspective [and]...fresh and balanced voices to a sometimes parochial discussion… It is both very readable and very well edited; with the articles fitting together more like a puzzle than a mélange of individual contributions. Not to be read only once or in one sitting, this journal is an important reference for those interested in how business and government can maintain the benefits of the first industrial revolution while dramatically reducing the burden those benefits place on the underlying living systems that need to be sustained during the next industrial revolution."

The *JIE* has been rated as the top journal devoted to industry and the environment by North American management researchers (Cohen, 2005).

The *JIE* was chosen in 2005 for inclusion in the Science Citation Index Expanded, maintained by Thomson Reuters/ISI. This citation index tracks the pattern of citations (referencing) among the top peer-reviewed journals worldwide. Only 10% of the journals that apply for inclusion are accepted. Its journal impact factor, a measure of the frequency with which the articles of a journal is cited in other work, was 2.7 for 2013.

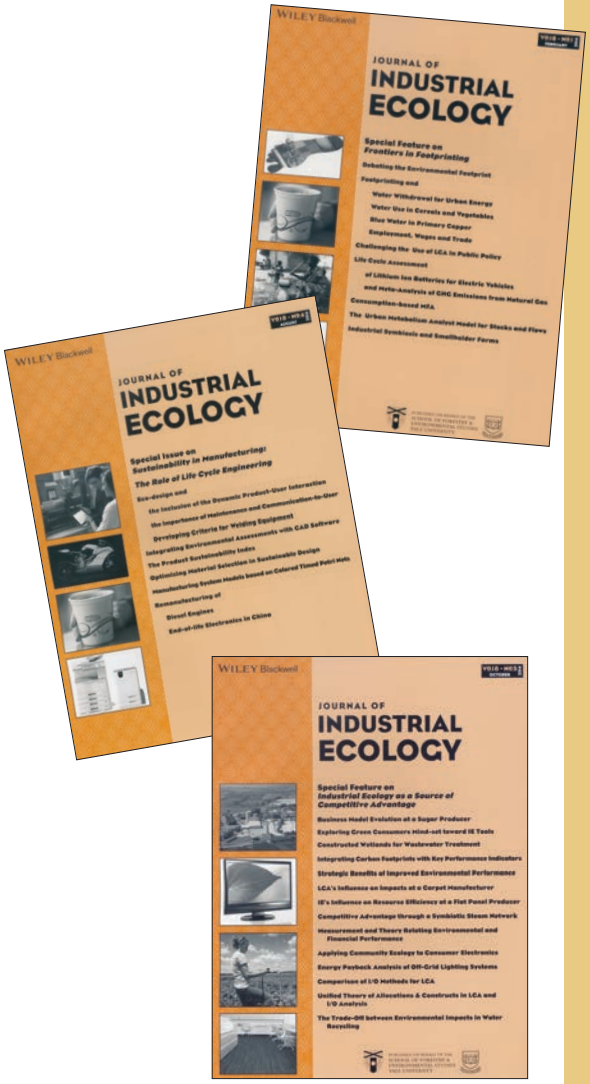
Since its founding, the *JIE* has evolved and grown. What began as a print quarterly available only by subscription has evolved into a hybrid open access bimonthly journal available in print and electronic form. In this evolution, the *Journal* progressed from distribution in print form in a few hundred libraries to electronic distribution through more than 7,000 institutional sites around the world. Because of the important role of China in the global environment and emphasis in China on environmental strategies closely aligned with industrial ecology, the *JIE* translates abstracts for all articles into Chinese, extending the reach of the *Journal* and increasing the dissemination of industrial ecology research to new audiences.

The *JIE* has played a leadership role in shaping the discourse and research agenda on many issues. An early special issue on e-commerce, the internet and the environment catalyzed research on the environmental dimensions of the shift to a digital economy. A special issue on nanotechnology and the environment highlighted the impacts of nanomanufacturing, previously thought to be benign because of the prospect of creating nanomaterials "one atom at a time." Articles on corn ethanol and on electric vehicles generated intense national and global debate

...an important reference for those interested in how business and government can maintain the benefits of the first industrial revolution while dramatically reducing the burden those benefits place on the underlying living systems that need to be sustained during the next industrial revolution.

ACHIEVEMENTS

on both the environmental benefits of those technologies and the methodologies used to assess them. An especially central contribution of the *JIE* has been its role helping to define and grow the field.



SPECIAL ISSUES OF THE *JOURNAL OF INDUSTRIAL ECOLOGY*

The *Journal of Industrial Ecology* has published over 1,190 papers in 17 volumes since its founding. The breadth and diversity of topics within *Industrial Ecology* is reflected by the special issues of the *Journal*.

- The Industrial Ecology of Paper and Wood: 1(3) *(Reid Lifset)*
- E-Commerce, the Internet, and the Environment: 6(2) *(David Rejeski)*
- Biobased Products: 7(3–4) *(Robert Anex)*
- Consumption and Industrial Ecology: 9(1–2) *(Edgar Hertwich)*
- Eco-efficiency: 9(4) (*Gjalt Huppes, Masanobu Ishikawa)*
- Nanotechnology and Industrial Ecology: 12(3) *(Roland Clift, Shannon Lloyd)*
- Materials Use Across World Regions: 12(5–6) *(Helga Weisz, Heinz Schandl)*
- Complexity and Industrial Ecology: 13(2) *(Gerard Dijkema, Lauren Basson)*
- Applications of Material Flow Analysis: 13(5) *(Claudia Binder, Ester van der Voet, Kirsten Sinclair Rosselot)*
- Sustainable Consumption and Production: 14(1) *(Arnold Tukker, Maurie Cohen, Klaus Hubacek, Oksana Mont)*
- Environmental Applications of Information and Communication Technology: 14(5) *(Eric Masanet, H. Scott Matthews)*
- Industrial Symbiosis: 16(1) *(D. Rachel Lombardi, Donald Lyons, Han Shi, Abhishek Agarwal)*
- Meta-Analysis of Life Cycle Assessments: 16(Supp. 1) *(Miguel Brandão, Garvin Heath, Joyce Cooper)*
- Greening Growing Giants: 16(4) *(Seiji Hashimoto, Marina Fischer-Kowalski, Sangwon Suh, Xuemei Bai)*
- Sustainable Urban Systems: 16(6) *(Christopher Kennedy, Lawrence Baker, Shobhakar Dhakal, Anu Ramaswami)*
- Extended Producer Responsibility (Special Feature): 17(2) *(Reid Lifset, Atalay Atasu, Naoko Tojo)*
- Frontiers in Footprinting (Special Feature): 18(1) *(Reid Lifset)*
- Sustainability in Manufacturing: The Role of Life Cycle Engineering: 18(4) *(Christoph Herrmann, Michael Hauschild, Tim Gutowski, Reid Lifset)*
- Industrial Ecology as a Source of Competitive Advantage (Special Feature): 18(5) *(Andrew Hoffman, Peter Wells, Charles Corbett, Nitin Joglekar)*

PROGRAMS IN INDUSTRIAL ECOLOGY

Over four hundred courses in IE are taught at universities around the world. Here we highlight several universities that have gone further, by establishing programs or certificates in IE. (Further programs are listed by Finlayson et al, 2014).

Beijing University of Science and Technology (School of Metallurgical and Ecological Engineering Master's Degree of Industrial Ecology)

The IE program is hosted in the School of Metallurgical and Ecological Engineering, which consists of the Department of Ecological Science and Engineering, the Department of Physical Chemistry, the Department of Ferrous Metallurgy and the Department of Non-ferrous Metallurgy, together with the Institute of Historical Metallurgy and Materials and an Experiment Center.

Chalmers University (Master's Program in Industrial Ecology for Sustainable Development)

The program aims are to equip students with: i) the competencies, knowledge and tools needed to analyze environmental impacts and resource constraints; ii) the ability to plan, lead, and evaluate projects in application areas such as product development, land and resource use, energy systems, and large-scale urban planning.

Industrial Ecology provides a solution-oriented engineering approach to environmental and sustainability problems. Hence, while it is important for graduates of the program to have gained a broad understanding of environmental problems in nature, they should become experts in analytical tools that facilitate the suggestion of relevant measures or policies.

Engineers from the program have obtained jobs in industry, environmental consultancy firms, governmental agencies and research. Industrial sectors such as energy, automobile, furniture, green buildings and process industry have employed graduates of the program in positions such as environmental strategy analyst, project leaders at environmental divisions and in technology development. Environmental consultancy firms have hired graduates for life cycle assessment, systems analyses of energy resources and waste. Some students now work in governmental agencies: e.g. Swedish Energy Agency, Swedish Environmental Technology Council. Other students have continued within academia both at Chalmers (Physical Resource Theory, Environmental Systems Analysis, Energy Technology, Logistics and Transportation, Shipping and Marine Technology) and other internationally known institutions.

PROGRAM STRUCTURE

The first semester consists of compulsory courses including Sustainable Development, Science of Environmental Change, Environmental Systems Analysis and Technical Change and the Environment. In the second and third semesters students choose at least four out of ten semi-compulsory courses. These courses are broadly divided into two different tracks depending on interest:

- Company level courses (e.g. Environmental Management and Life Cycle Analysis).
- Society level courses (e.g. Environmental Policy Instruments and Sustainable Energy Futures).

The program ends with a master's thesis either in industry or in a research department. Several students from the program have also conducted master's theses in the form of Minor Field Studies (MFS) in developing countries.

For further details see: *http://www.chalmers.se/en/education/programmes/masters-info/Pages/Industrial-Ecology.aspx*

Erasmus Mundus (Master's Program in Industrial Ecology)

The objective of the "Erasmus Mundus Master's Program in Industrial Ecology" is to enable students to understand and propose solutions that support the transition towards a sustainable society. With teaching through an international consortium, a unique view on the field of "Industrial Ecology" at local, European and global levels is possible. Students learn a methodologically correct approach to complex interdisciplinary issues and are introduced to specific subject areas by experts of the partner universities. Thereby, a strong emphasis is placed both on research and practical problem solving applications for sustainable development.

After completing this study program should be able to:

- Understand and to adequately describe the dynamics, complexity and interrelations between natural, technical, social and economic processes and systems in terms of sustainable development.
- Apply and improve state-of-the-art methods and techniques in the field of "Industrial Ecology". This particularly includes methods of system analysis, "Life Cycle Assessment," Material Flow Analysis, Input-Output Analysis, Stakeholder Analysis, "Transition Management", System Dynamics, "Agent Based Modeling" and the implementation, monitoring and management of innovation processes.
- Analyze problems in the field of Industrial Ecology such as waste, resource and technology management from a multidisciplinary perspective.
- Identify, analyze and assess environmental effects of processes, products, projects and strategies.
- Apply general academic skills for the Industrial Ecology context, such as the use of research methods and tools from statistics, data collection, modeling techniques, IT, as well as the critical application and evaluation of theories, concepts and principles.
- Clearly prepare the results in written form and for presentations for academic and non-academic target groups.
- Apply their knowledge and scientific skills on complex issues in inter- and trans-disciplinary teams, furthermore to demonstrate necessary social skills (e.g. writing, discussion, conflict management, teamwork, project management) and therefore to be able to contribute to a transition towards a sustainable society.

Graduates of the program have gone on to careers in the following areas:

- Administration and management
- Environmental and management consultancy
- Industrial companies (e.g. product design, waste management)
- International organizations
- Quality assurance
- Service industry (e.g. tourism)
- Scientific Research
- Teaching

PROGRAM STRUCTURE

The Program includes six specialization modules taught at partner universities:

- University of Graz (Austria):The human dimension of Industrial Ecology – Decision-making models and sustainability assessment
- Leiden University, Delft University of Technology (The Netherlands): Industrial Ecology methods and tools, in particular modeling certain material systems
- Chalmers University of Technology (Sweden): Sustainable technical systems
- Asian Institute of Technology (Thailand): Asian perspective on Industrial Ecology, technology issues in Industrial Ecology
- Rochester Institute of Technology (U.S.A.): Alternative energy and decision analysis
- Waseda University (Japan): Industrial Ecology methods based on input output analysis, with special emphasis on waste and resource management

Leiden University and Delft University of Technology (Joint Program in Industrial Ecology)

The Master of Science in Industrial Ecology (IE) started in September 2004 and was accredited in February 2011. The number of students graduating grew from 15 in 2011–2012 to 21 in 2012–2013. The incoming class in 2012–2013 had 43 students, increasing to 53 students in 2013–2014.

Industrial Ecology graduates find employment opportunities throughout business, industry and government, as well as in non-governmental organizations, universities and research institutes. They operate as mediators, system designers, innovators and scientific researchers. They are primarily engaged in activities designed to encourage people at all levels of society to consider adopting sustainable practices and to initiate change in existing patterns of production and consumption. Graduates of the program typically secure suitable employment within one year after graduating.

Examples of positions held by graduates include:

- Policy researcher at Netherlands Assessment Agency
- Procurement manager Shell
- Consultant Natural Resources Defense Council
- Corporate Management Trainee Nuon Energy
- Consultant Climate, Energy and Sustainable Building Milieudienst Zuidoost Utrecht
- Researcher at Rathenau Institute
- Partner at Ecomatters
- Consultant IMSA Amsterdam

PROGRAM STRUCTURE

The study program consists of a two-year curriculum. The first year focuses on the core concept of Industrial Ecology. Courses and modules are practice-focused and are taught and examined in classes by means of project teamwork, presentations and written examinations. The program provides possibilities for exchange with foreign universities and companies. The second year of the program consists of compulsory group projects and an individual research trajectory culminating in an M.Sc. thesis. During the group projects multidisciplinary teams of students have the task of analyzing and developing solutions for specific industry related sustainability problems. In these project groups students learn to analyze a problem from different points of view and discover the added value of working in multidisciplinary teams.

Industrial Ecology graduates find employment opportunities throughout business, industry and government, as well as in non-governmental organizations, universities and research institutes

Courses First Year

- General Introduction to Industrial Ecology
- Renewable Energy Systems
- Fundamentals of Systems, Data, Models and Computational Thinking
- Analytical Methodologies and Tools
- Social Systems – Policy and Management
- Urban Environments and Infrastructures
- Sustainable Innovation and Social Change
- System Earth
- Design of Sustainable Technological Systems
- Specialization Modules

Courses Second Year

- Interdisciplinary Project Groups
- Thesis Preparation Module
- Thesis Research Project
- Specialization Modules: Advanced Course on LCA

For further information see: *http://www.industrialecology.nl*

Northeastern University (China)

Highlights of Program

- In December 2013, "Industrial Ecology-Tunneling through the Environmental Mountain" was first offered on the Internet as a State Open Class.
- The program graduates an average of 10 students with Masters degrees each year, with a smaller number working towards the Ph.D.
- Northeastern collaborates with IE departments in other universities including Yale University, the University of Manchester, the University of Tokyo, Ritsumeikan University, Nagoya University, National Institute for Environmental Studies (NIES), the University of Melbourne, Tsinghua University, University of Chinese Academy of Sciences.

- Graduates from the program find employment opportunities in universities, research institutes on environment or iron & steel production, and in government.

Norwegian University of Science and Technology (Master's Degree Program in Industrial Ecology)

Norwegian University of Science and Technology (NTNU)'s Masters program provides students with the ability to apply the analytical tools of Industrial Ecology to a wider range of environmental issues and across different scales, from individual production processes through value chains to national economies. Analysis serves to quantify environmental impacts, understand how environmental stresses are produced, and to evaluate proposed solutions or alternative courses of action. Issues in the industry-environment context that are relevant are: energy, waste, industrial parks and networks, as well as sustainable production and consumption. The students are equipped for jobs in research, policy analysis (government, civic actors), and technical analysis in large companies and consultancies.

PROGRAM STRUCTURE

The two year course of study consists of the following elements:

- Core courses in Industrial Ecology, taken by all students in the program.
- Elective courses allowing the students to acquire additional skills or factual knowledge in a field directly relevant to their Master's thesis.
- A project and a Master's thesis.

Available courses include:

- Industrial Ecology
- Life cycle assessment and eco-efficiency
- Environmental management and corporate social responsibility
- Input-output analysis, trade and environment
- Energy and environmental consequences
- Environmental politics
- Material flow analysis
- Eco-design
- Environmental and resource economics

For further details see: *http://www.ntnu.edu/studies/msindecol/*

Shandong University

In 2008, Professor Wennersten helped Shandong University (SDU) establish the industrial ecology major, the first in China. The Joint Research Centre for Industrial Ecology, JRCIE, is a joint venture between SDU and KTH Stockholm. Located in new facilities at the Shandong University campus, JRCIE is developing activities in the areas of education, research & development as well as commercial applications of sustainable technologies.

University of Michigan (Graduate Certificate Program in Industrial Ecology)

The primary objective of the Program in Industrial Ecology (PIE) is to provide University of Michigan graduate students fundamental skills in, and knowledge of, industrial ecology methods and applications. PIE's certificate complements any field of study by providing specialization in technological and industrial innovation, consumer behavior and consumption patterns, policy and regulatory issues, and economic factors and market forces to achieve more sustainable systems. Participating students will be better prepared to design and manage natural and industrial systems to meet human needs in an environmentally, economically and socially sustainable manner.

PROGRAM STRUCTURE

The certificate in IE at the University of Michigan requires completion of five courses:

- Industrial Ecology *(core course)*
- System Analysis and Sustainability *(one selection from: Environmental Impact Assessment; Biogeochemical Cycles;*

Systems Thinking for Sustainable Development and Enterprise; Sustainable Design of Technology Systems; Environmental Systems Analysis; Consumption, Trade, and Environ. Input-Output Analysis; Life Cycle Assessment: Human Health and Environ Impacts)

- Energy Systems *(one selection from: Sustainable Energy Systems; Transportation Energy & Climate; Energy Infrastructure Systems)*
- Environmental Policy and Strategies *(one selection from: Environmental Law; Natural Resources Conflict Management; Strategy for Sustainable Development; Sustainable Development: Resolving Economics and Environ Conflicts; The Politics of Environmental Regulation; Energy Markets and Energy Politics)*
- Risk and Economic Analysis *(one selection from: Principles of Risk Assessment; Environmental Economics: Quantitative Methods and Tools; Advanced Natural Resource Economics; Environmental Energy and Resource Economics; Energy Economics and Policy; Ecological Risk Assessment)*

For further information see: *http://industrialecology.umich.edu/*

Yale University, Center for Industrial Ecology (Master of Environmental Management, Specialization in Sustainable Urban and Industrial Systems)

The specialization in Sustainable Urban and Industrial Systems seeks to improve understanding of how urban and industrial systems operate, their underlying drivers, and their impacts on society and the biosphere. It will also point students toward the many opportunities for technological, policy, and market interventions in urban and industrial settings that will be critical to achieving global sustainability through focus on systems approaches.

The topics of this Specialization overlap and are intended to be integrative but are broken down into three areas that together make up the core material:

- Urban systems advance understanding of urbanization as a coupled human-natural process of change and transformation from local to global scales.
- Industrial systems draw on the School's leadership in industrial ecology and industrial environmental management including green chemistry and green engineering, technology development, and resource management.
- Business systems provide a financial and market-based view crucial to understanding current and future states of urban and industrial development *(see also the Specialization in Business and the Environment)*.

PROGRAM STRUCTURE

Students intending to specialize in Sustainable Urban and Industrial Systems are recommended to take three or more courses in their topical area of greatest interest, at least two courses in their area of secondary interest, and one course from the remaining area. These courses are in addition to the Foundations courses, an Integrative Frameworks course, and at least one Capstone course.

Industrial Systems

Green Engineering and Sustainable Design

Energy Systems Analysis

Industrial Ecology

Managing Resources

Energy Technology Innovation

Advanced Industrial Ecology Seminar

Life Cycle Analysis Practicum

Supply Chain Management

Urban Systems

Urbanization, Global Change, and Sustainability

Ecological Urban Design

Mitigating and Adapting to Climate Change in Urban Areas

Seminar in Research Analysis, Writing and Communication

Introduction to Urban Design

Introduction to Planning and Development

Business Systems

Corporate Environmental Management and Strategy

The New Corporate Social Responsibility: Public Problems, Private Solutions, and Strategic Responses

Private Investment and the Environment: Legal Foundations and Tools

Green Markets: Voluntary and Information-based Approaches to Environmental Management

Business and the Environment Consulting Clinic

Financing Green Technologies

For further details see *http://environment.yale.edu/academics/degrees/mem/urban-industrial/*

CAREER PATH AND STATEMENTS FROM INDUSTRIAL ECOL

Eight students were interviewed on how their training in Industrial Ecology has helped their careers.

BEN ZHU

Ph.D. TU Delft, the Netherlands/Erasmus Mundus M.Sc. Industrial Ecology (MIND)

After several years of intercultural experiences in China, Scotland, Austria, U.S. and the Netherlands, being intrigued by the topics of industrial ecology, sustainability and renewable energy, Ben is currently a Ph.D. candidate at Delft University of Technology, focusing on building an industrial symbiosis data repository.

AMANDA LOUISE HILL

Ph.D. Aalborg University, Denmark/ M.Sc. Environmental Management and Sustainability Science, Aalborg University, Denmark

Amanda grew up in Adelaide, Australia, and even from a young age was interested in waste management. After majoring in Biology, she became interested in the interactions of humans industrial and agricultural systems with the natural environment. Moving to Denmark, she wanted to help find ways to allow industry and agriculture to continue developing, without increasing the ecological burden.

ANGELICA MENDOZA BELTRAN

Ph.D. Leiden University, the Netherlands/ M.Sc. Industrial Ecology, Leiden University, the Netherlands

Angelica completed her studies in Environmental Engineering at Los Andes University (2006) in her home city of Bogota, Colombia. After her M.Sc. degree in Industrial Ecology at Leiden University she worked at the Netherlands Environmental Assessment Agency (PBL) as a junior Policy Researcher (2012). There, she was involved with the development and applications of the IMAGE Integrated Assessment Model.

SASKIA VAN GENDT

Captain Planet for Method, San Francisco, U.S.A./M.Sc. Industrial Ecology, Leiden University/TU Delft, the Netherlands

Saskia studied industrial ecology at Leiden and Delft Universities and environmental science at Northwestern University. She worked for six years at the U.S. Environmental Protection Agency, where she led material sustainability projects in packaging, building products, and food waste. Saskia is currently with Captain Planet for Method, a green cleaning company based in San Francisco.

MAX SONNEN

Co-Founder of Ecomatters, the Netherlands/M.Sc. Industrial Ecology, Erasmus University, the Netherlands

Max obtained his bachelors degree in Systems Engineering, Policy Analysis & Management at the Delft University of Technology. After his M.Sc. in Industrial Ecology he founded Ecomatters, a company which develops tools and implements projects in the field of (product) life cycle management. Max' focus mainly lies on the implications for strategy, economics and IT aspects.

JULIAN PATRON COPPEL

CTS EMBARQ Mexico World Resource Institute / European Master's on Sustainability, Politecnica de Catalunya UPC, Barcelona, Spain with an exchange at Royal Institute of Technology (KTH) Stockholm, Sweden

Julian is an industrial and systems engineer with professional experience in manufacturing from the private sector, and fisheries management and regulation from the government

sector. In recent years he has worked on urban mobility and urban development projects for EMBARQ / World Resources Institute. His interests lie within the branches of life cycle assessment, energy systems, and mostly urban metabolism and development.

JOHAN BERG PETTERSSEN

Senior advisor and Partner at Miljøsystemsanalyse (MiSA)

Johan graduated in 2003, from NTNU with a Master in Biotechnology. He then completed a Ph.D. in Industrial Ecology in 2007 at the Department of Energy and Process Engineering.

ZHU LIU

Giorgio Ruffolo Fellow in the Sustainability Science Program and the Energy Technology Innovation Policy project in Harvard University.

Zhu's research is mainly about energy sustainability in China. Specifically, Zhu's work quantifies carbon emission and explores options for a low carbon pathway for China's sustainable development. He received his Ph.D. in Ecology from the Chinese Academy of Sciences (CAS) in 2013. He also holds a Bachelor's degree in Geology from Northwest University (2007) and a Master's degree in Ecology from China Agricultural University (2009).

What were your favorite IE classes during your study?

ANGELICA: Difficult question. Sometimes what you like most is not what you are best at ;) … I enjoyed a lot the lessons on social sciences for IE. They really broaden my previous engineering background and made me realize that real understanding of environmental issues needs a multidisciplinary approach. Also the analytical tools and modeling classes were very interesting for me and gave me a more robust framework for assessment of environmental problems and systems.

SASKIA: The fundamental courses about system flow analysis and life cycle analysis laid an important foundation for the principles of IE. Those courses helped me reframe my approach to environmental challenges to consider effects and relationships within larger environmental and economic systems. I also took a class on the built environment which ultimately inspired me to work on green building.

How did your training in IE help your later career development? / How do you apply your training in IE to your daily work?

AMANDA: Currently I am writing a Ph.D. about waste management at Aalborg University in Denmark, and exploring the use of IE as a waste management strategy for industrial waste. So I use my IE training every day. I also feel that the understanding of the biological metaphor and the cyclic, systems thinking is beneficial to all areas of waste management. So even when I am working with household waste, I try to see the systems through an IE lens. I also have contacts with some local

Those courses helped me reframe my approach to environmental challenges to consider effects and relationships within larger environmental and economic systems.

industry leaders who have established a network to try to encourage IE activities here in Aalborg.

ANGELICA: On my first job as a junior policy researcher, I realized that I could actually apply many of the concepts and tools I learned when I was an IE student. I realized that my conceptual background was very broad, from chemical processes and technologies to renewable energies and system earth dynamics. I was able to understand what climate policies were referring to and what they were intended to do in society and therefore I was able to research on whether they were sufficient to actually mitigate climate change at a global scale. Also, I realized that technical skills that I learned as an IE student like computer programing, data management and environmental modeling were an asset for my daily work.

MAX: I run, together with a partner who is a toxicologist, a consultancy firm in Sustainability and Chemical Safety. We do a lot of sustainability strategy implementation and environmental assessment all based on quantitative assessment such as LCA. So from that sense I use the actual

knowledge and skills I learned at IE on a daily basis.

JOHAN: The systems perspective that we learned in IE is the basis for my current position and the backbone of all my work. To understand how all parts of a system are connected to each other, and have tools and a language to describe these relations and the mechanisms involved is useful in any job.

To understand how all parts of a system are connected to each other, and have tools and a language to describe these relations and the mechanisms involved is useful in any job.

What are your mid/long term career objectives?

BEN: I believe the combination of the strengths of human brains and machines will power cutting-edge productivity. So I will try to practice in the field of IE 2.0, linking information technology with IE in an industrial level. With my background, I also hope to implement IE disciplines in developing countries, aiming at merging bottom-up initiatives with top-down strategies.

JULIAN: I would like to work as a consultant for a firm specializing in integrated sustainability with a system vision; such as Except Integrated Sustainability. At some point I would like to pursue a Ph.D., not on the academic branch though; personally I find very interesting sustainability projects where there is an intersection between academia, government initiatives and the private sector, which at the end of the day is the one who capitalizes projects and makes things happen with a high efficiency degree. As of my interests within IE and its broad subjects, I am very attracted towards urban metabolism and data visualization.

JOHAN: I enjoy practical LCA and systems analysis work and hope to be doing more of it in the future, and perhaps less of the management tasks. Since cofounding our own consultancy MiSA I have learned that the real value of tools and research lies with the user and how they are used. My current main objective is to expand the understanding and use of the IE perspective outside the traditional community.

LIU: It is a wonderful journey doing research, and I have many (well) minded friends; I would love to be a researcher.

Do you have some good advice for current students in IE?

BEN: Think proactively and act practically.

SASKIA: Maybe not advice but perspective: When I was studying industrial ecology, it seemed fairly abstract. But IE is actually a very practical study. Once you start applying it to a particular industry or system, it's a very useful skill that lots of companies value.

JULIAN: Believe in what you do and make it fun; no need to make it boring. Few

I also hope to implement IE disciplines in developing countries, aiming at merging bottom-up initiatives with top-down strategies.

people in the world are in our positions as system thinkers going beyond disciplinary boundaries. There is a whole new emerging market for us out there, not because it is something fashionable as some marketers take advantage of, but because there is an urgent need for innovation towards human welfare improvement. We have the insight and tools on how to achieve it.

LIU: Keeping doing right things, making a difference and contributing to a better future.

THE LAUDISE YOUNG RESEARCHER PRIZE

The Laudise Prize is awarded for outstanding achievements in industrial ecology by a researcher under the age of 36. Endowed by AT&T in memory of Robert Laudise, past recipients are:

2003 EDGAR HERTWICH

Since winning the inaugural Laudise Prize, Edgar Hertwich has become Professor of Energy and Environmental Systems Analysis at the Norwegian University of Science and Technology. His research has included work on life cycle assessment of energy technologies; modeling and accounting of emissions and resource use related to consumption and international trade; the carbon footprint of nations; risk analysis; and life cycle impact assessment in the marine environment. Edgar Hertwich was the lead author of the UN International Resource Panel 2009 report on The Environmental Impacts of Production and Consumption, and leads two other groups of the Panel. He was also lead analyst for the Global Energy Assessment of the International Institute of Systems Analysis. He is a member of the editorial board of the *Journal of Industrial Ecology* and has co-authored more than 50 peer-reviewed journal articles, many which have appeared in leading journals. Hertwich earned a Ph.D. in energy and resources from the University of California, Berkeley.

2005 ARPAD HORVATH

Arpad Horvath is a Professor in the Engineering and Project Management Program and in the Energy, Civil Infrastructure and Climate Program in the Department of Civil and Environmental Engineering at UC Berkeley. He has Ph.D. and M.S. degrees in Civil Engineering from Carnegie Mellon University, and a Diploma in Civil Engineering from the Technical University of Budapest (Hungary). His research interests are in developing methods and tools for life cycle assessment of civil infrastructure systems and other industries. His research has focused on the environmental implications of transportation systems, buildings, construction, water and wastewater systems, and various service industries, and life cycle assessment modeling using hybrid methods, environmentally augmented economic input-output analysis, and environmental performance measurement. Arpad Horvath is the director of the Consortium on Green Design and Manufacturing (CGDM), and Associate Editor of the ASCE's *Journal of Infrastructure Systems*.

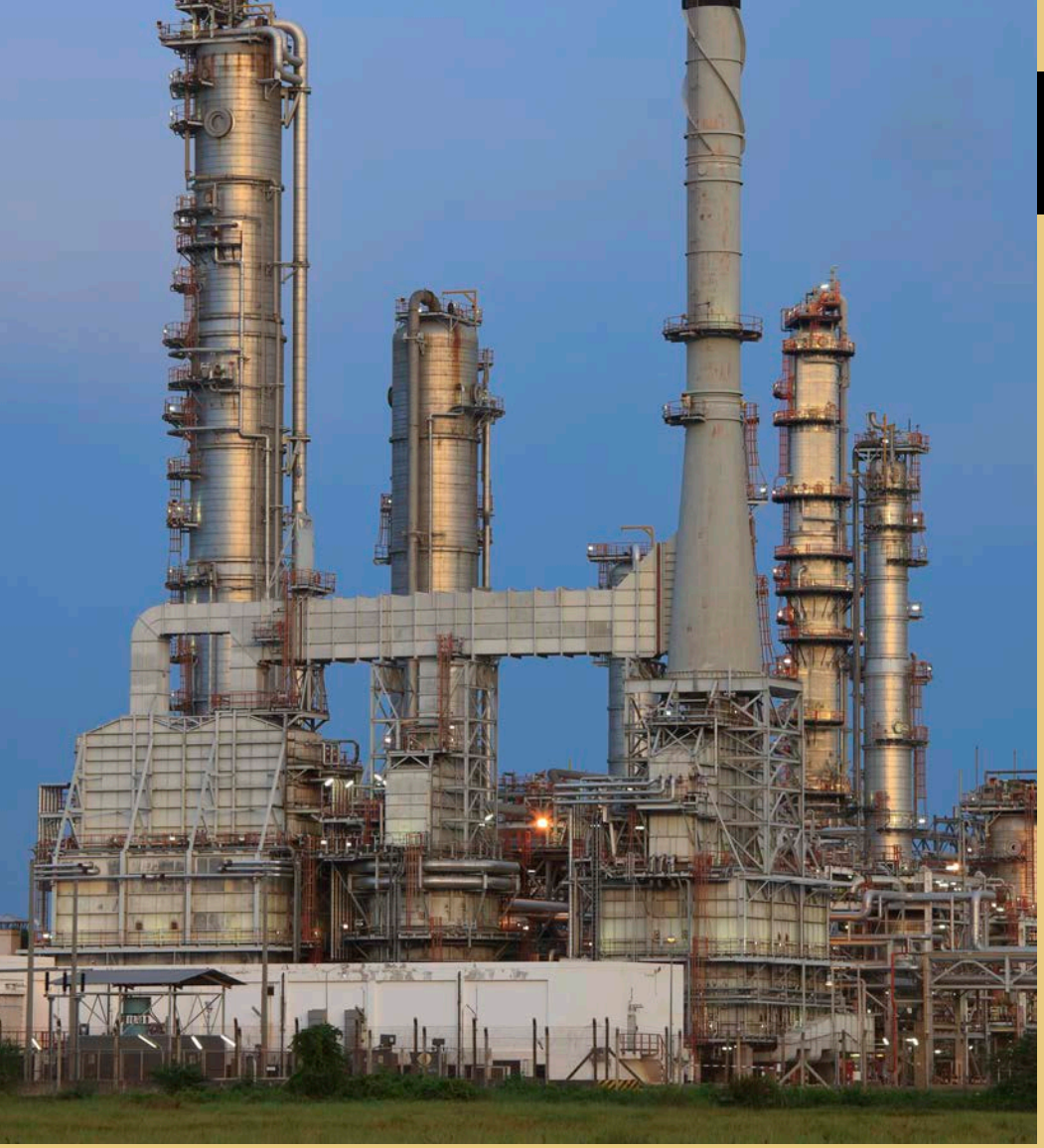
2007 SCOTT MATTHEWS

Scott Matthews is Professor in the Department of Civil and Environmental Engineering and the Department of Engineering and Public Policy at Carnegie Mellon University. He is also Research Director of the University's Green Design Institute. His research and teaching focuses on valuing the socioeconomic implications of environmental systems, sustainable engineering, and industrial ecology. His work facilitates environmental decision making under uncertainty via large datasets, computation, and visualization methods. He has contributed to the development of tools for environmental and energy life cycle assessment of products and processes (such as the EIO-LCA model), estimating and tracking environmental effects across global supply chains (such as carbon footprinting), and the sustainability of infrastructure systems. Dr. Matthews has served as chair of the Committee on Sustainable Systems and Technology with the Institute of Electrical and Electronic Engineers and on the Executive Committee for the American Center for Life Cycle Assessment. He participated in the National Research Council study on the Hidden Costs of Energy and is a member of the NRC Board on Environmental Studies and Toxicology.

He was awarded the Best Policy Paper in 2008, by *Environmental Science & Technology* (ES&T) for his article (with C.L. Weber) "Food-Miles and the Relative Climate Impacts of Food Choices in the United States."

2009 SANGWON SUH

Dr. Sangwon Suh obtained his Ph.D. *(cum laude)* for his dissertation, "Materials and Energy Flows in Industry and Ecosystem Networks" at Leiden University in the Netherlands in 2004. Following a position at the University of Minnesota in 2005, he joined the University of California, Santa Barbara (Bren School) in 2010. Sangwon Suh was appointed as a member of UNEP's International Resources Panel in 2009, and has been the coordinating lead author of the Assessment Report 5 by the Intergovernmental Panel on Climate Change (IPCC). He is an Associate Editor of the *Journal of Industrial Ecology* and was elected Chair of the 2012 Gordon Research Conference on Industrial Ecology. He serves on merit review committees of the U.S. National Science Foundation, U.S. Department of Energy, U.S. Department of Agriculture and the Swiss National Science Foundation. Dr. Suh



has authored, co-authored or edited three books and over 60 peer-reviewed journal articles, and his publications include some of the most widely cited in the field.

2011 ANDERS STRØMMAN

Professor Anders Hammer Strømman conducts research on environmental assessment of Energy and Transport systems on which he has published more than 40 peer-reviewed journal articles. He is currently a contributing author to the Working Group III of the 5th assessment report of the IPCC. On a daily basis he teaches graduate courses in Life Cycle Assessment and Environmental input-output analysis for the students of the Industrial Ecology and Energy & Environment study programs at NTNU.

2013 MATTHEW ECKELMAN AND ALYSSA KENDALL

Matthew Eckelman is an Assistant Professor at Northeastern University in Civil and Environmental Engineering. His research covers life cycle assessment and systems modeling of the environmental impacts of chemicals and emerging materials, such as nanomaterials, biofuels and biobased chemicals. Dr. Eckelman consults regularly on sustainability-related projects with a range of businesses, institutions, and government agencies, with a particular focus on industrial chemicals and formulated products. He also sits on the Advisory Board of the Resources Optimization Initiative in Bangalore, India. Dr. Eckelman previously worked in the Massachusetts State Executive Office of Environmental Affairs and Design that Matters, a non-profit product design company, and was a Peace Corps science instructor in southern Nepal for several years. He received a doctorate in Chemical and Environmental Engineering from Yale.

Alissa Kendall joined the University of California Davis as an Assistant Professor in Civil and Environmental Engineering in the summer of 2007 after completing a multidisciplinary Ph.D. at the University of Michigan. Kendall received the 2013 Laudise Prize (jointly with Eckelmann) for her work on life cycle assessments of biofuel production pathways, agricultural systems, vehicles, and transportation infrastructure. The prize additionally commends Kendall for her ongoing research on carbon accounting practices and the role of LCA in policy.

FUNDING INDUSTRIAL ECOLOGY RESEARCH

Industrial Ecologists have conducted numerous high impact research projects over the years, with funding from both public and private sectors. No comprehensive survey of IE research funding has been undertaken; so a few examples of larger, notable projects are highlighted below:

AUSTRALIA

A consortium of four universities and industry partners is conducting a project on Integrated Carbon Metrics, in which a multi-scale life cycle approach is being used for assessing, mapping and tracking carbon outcomes for the Built Environment. The project leader is Tommy Wiedmann at the University of New South Wales, with collaborators at University of Melbourne, University of South Australia, and CSIRO. Industry partners include: AECOM, Aurecon, Bluescope Steel, and Sydney Water. Funding of $1.6 million for this four year project (2014–2018) comes from the Cooperative Research Centre for Low Carbon Living.

Another exciting project is the development of the Industrial Ecology Virtual Laboratory (IE Lab). This new electronic research platform helps researchers address the complex environmental and economic interactions in contemporary Australia. Based on environmentally extended multi-region input-output (MRIO) analysis the virtual laboratory enhances analytical capabilities in environmental life cycle assessment (LCA), environmental footprinting and other quantitative approaches to environmental and sustainability impact assessment. Funding of AU $1.1 million for the IE Lab comes from the Australian Government's NeCTAR scheme (2013–2014). Phase 1 of the lab development is led by Manfred Lenzen from University of Sydney, with Tommy Wiedmann (UNSW) managing the operational phase. Other collaborators on the IE Lab (S. Kenway, P. Lant, R. Crawford, P. Daniels, H. Schandl, D. Webb, and J. Boland) come from six other Australian universities and research institutions.

AUSTRIA

Karl-Heinz Erb, at the Institute of Social Ecology in Vienna, is leading an integrated socioecological study of land use intensity. The project (LUISE) applies industrial ecology concepts such as the analysis of biophysical resource flows to land use science. It aims to deepen our understanding of changes in land use intensity in terms of social, economic and ecological preconditions and implications. The project is funded by the European Research Council with a grant of approximately €1 million.

CHINA

The Chinese Government is investing heavily in IE research. One example of this is the establishment of the "State Environmental Protection Key Laboratory of Eco-industry" which is supported by the Ministry of Environment Protection to promote the development of Industrial Ecology in China. The laboratory was jointly established by Northeastern University, Tsinghua University and the Chinese Research Academy of Environmental Sciences, and now employs more than 30 full-time researchers, including three members of the Chinese Academy of Engineering Prof. Yi Qian, Prof. Yong Jin and Prof. Zhongwu Lu. Since its establishment in 2002, the Laboratory has led more than $30 million projects including hundreds of eco-industrial parks and circular economy planning projects.

Further examples are two projects led by Geng Yong, Professor on circular economy and industrial ecology, at the Institute of Applied Ecology, Chinese Academy of Sciences. Geng received 1.4 million RMB (2014–2017) from the Natural Science Foundation of China (National Research Grant for Distinguished Young Scientists) for the project: Resource Efficiency and Environmental Management Policy Research. In an earlier project: The Evolution, Evaluation and Optimization Pathway for Industrial Ecosystems (2011–2014) he received 1.5 million RMB from the Natural Science Foundation of China (National Key Research Grant).

Jiansu Mao, Professor of Industrial Ecology at Beijing Normal University, has participated in several large collaborative projects in China. One from 2005 to 2010 was concerned with characterizing the ecology and evolutionary mechanisms of urban life ($4 million project led by Guo-he HUANG, funded by the Ministry of Environmental Protection and Ministry of Education). A second project from 2012 to 2014, with Linyu Xu, was part of the National Key Technology R&D Program on eco-urban planning and ecological construction, which received $1.5 million from the Ministry of Science and Technology.

KOREA

The Ministry of Trade, Industry and Energy in Korea has invested in several research projects relating to eco-industrial development. Hung-Suck Park, Professor in the Department of Civil and Environmental Engineering at the University of Ulsan is the General Director for the East South Region National Eco-Industrial

Park Initiative. From 2005 to 2014, the Initiative received a Fostering Energy and Resource Circulation Foundation Grant of 27 Billion KW. A further grant of 2.2 billion KW was awarded for a project: Building Green Construction Business Ecosystem using By-product Sulfur (Regional Innovation System Research Grant, 2011–2013)

MEXICO

Graciela Carrillo of the Universidad Autónoma Metropolitana, and Gemma Cervantes from Instituto Politécnico Nacional conducted an IE project in the Tampico Industrial Area of Mexico from 2010 to 2013. The project goals were to understand the reasons for successful industrial symbiosis in the area; and seek to improve upon it. Funding of approximately US$1.5 million was provide by the Science and Technology Council of Mexico.

NETHERLANDS

The Institute of Environmental Sciences, Universiteit Leiden (CML-IE), has participated in numerous large EU projects, such as:

- LC(S)A networking projects (at least 3)
- LCA case study projects (maybe as many as 10)
- EXIOBASE and CREEA: IOA methodology development and data collection projects
- Indicator development projects, such as DESIRE and EmInInn
- Climate and resource policy oriented projects, such as Resource Efficient Europe, CarbonCap, CECILIA and C2CA
- Impacts of biofuels projects: Dutch Science Foundation BBASIC and Biosolar cells.

Each of these projects has had a budget of several million euros with the CML-IE contribution varying from 100 to 800 k€. Altogether, the money from EU grants going to CML-IE over the last 15 years has been about 5 to 10 million euro. It also received two substantial grants from the Dutch Science Foundation on biofuels, as part of a larger consortium, where CML-IE brings in the sustainability analysis.

NORWAY

The Norwegian University of Science and Technology (NTNU) has a large and long-standing research program in Industrial Ecology, initially set up with funding from Norsche Hydro and other Norwegian industry. From 1998 to 2005, it received a large collaborative grant of about NOK 22 million for Industrial Ecology from the Research Council of Norway (Lead: Helge Brattebø). One example of its current research projects is a four year research project lead by Anders Hammer Strømman aiming to assess the environmental performance of carbon capture and utilization technologies. Working in collaboration with the Copernicus Institute at Utrecht University and Tel-Tek in Porsgrunn, the project is funded by Gassnova and other industrial partners.

SWITZERLAND

ETH Zurich has a joint project with Chalmers University (Sweden) and two consultancies (Aveny GmbH and GEO partner AG) on the life cycle management of wood resources in Switzerland. Lead by Stephanie Hellweg, the project received over $1 million from the Swiss National Science Foundation and is supporting three Ph.D. students and several PostDocs.

U.S.A.

From 1998 to 2005, the first National Science Foundation Integrative Graduate Education Research and Training grant on Industrial Ecology entitled "Environmental Manufacturing Management," was initiated at Clarkson University (Potsdam, NY) and later expanded to include the University of Illinois at Chicago. The PI was Thomas L. Theis, with funding of $1.95 million.

Among the projects currently funded by NSF involving collaborations among research teams from multiple disciplines, Faye Duchin, Professor of Economics at Rensselaer Polytechnic Institute, is a Principal Investigator on two. One is "A Regional Earth System Model of the Northeast Corridor: Analyzing 21st Century Climate and Environment," where the analysis focuses on scenarios including increased energy self-sufficiency for that 13-state region of the U.S. For the other, "Impacts of Global Change Scenarios on Ecosystem Services from the World's Rivers," her team is evaluating the global loss of dietary fish in terms of the cost of their replacement by other sources of animal protein.

A further $1.86 million NSF funded project "Biocomplexity in the bioeconomy" is studying the natural and industrial ecology of biobased products. The project lead is Robert Anex, University of Wisconsin Madison; with: Susie Greenhalgh, World Resources Institute; Lee Lynd, Dartmouth College; Cynthia Hinrichs, Pennsylvania State University; and Thomas L. Richard, Pennsylvania State University. Industry partners are DuPont Biobased Materials and the U.S. National Renewable Energy Laboratory.

RISING TO GLOBAL CHALLENGES

Industrial Ecology is at the forefront of efforts to address global environmental challenges. While much of the identification and explanation of issues such as climate change, biodiversity loss and disruption of nutrient cycles is conducted in the natural sciences, IE plays the role of linking these environmental stresses to human driving factors. It provides understanding of complex interactions and points the way to more sustainable ways forward.

The work of several industrial ecologists on **UNEP's International Resource Panel** demonstrates how IE is rising to address global environmental and economic challenges. Eight members of the Panel are ISIE members – authoring key reports on topics such as resource decoupling, metals, biofuels, global land use change, and environmental impacts of production and consumption. The first of the Panel's reports on Decoupling Natural Resource Use and Environmental Impacts from Economic Growth was led by former ISIE President Marina Fischer-Kowalski. The report describes how technological and systematic innovation, combined with rapid urbanization, offer an historic opportunity to turn decoupling from theory into reality on the ground. It became the most viewed UNEP report with more than 250,000 downloads.

Research on the **use, recycling, and stocks of metals** in society is important for long-term management of such often scarce resources. Tom Graedel, the founding President of ISIE, led the UNEP International Resource Panel work in this area. Important understanding of the potential for reusing, remanufacturing and recycling metals has been provided by Julian Allwood and colleagues at Cambridge University while Daniel Müller and colleagues at NTNU have contributed substantially to the understanding of metal stocks present in society to deliver services. They have developed approaches to metal demand and supply analysis which are now being used by large businesses for strategic decision making, especially in the aluminum industry.

With respect to **global climate change**, numerous members of the IE community led or contributed to chapters of the **IPCC 5th Assessment Report released** in 2014. These include chapters on Agriculture, Forestry, and Other Land Use Change (Haberl), Energy (Hertwich, Gibon), Settlements (Müller), the Bioenergy appendix of the Land Use chapter (Strømman, Cherubini, Bright), the Technical Summary (Hertwich) and Methodology annex (Müller, Hertwich, Haberl). There were many more IPCC authors among the IE community, such as Julian Allwood, Geng Yong, Jan Minx, John Barret, Sangwon Suh.

While much of the identification and explanation of issues such as climate change, biodiversity loss and disruption of nutrient cycles is conducted in the natural sciences, IE plays the role of linking these environmental stresses to human driving factors.

The **translation of IE principles into business** is one of the most important outputs of the field. An excellent example is the UK's National Industrial Symbiosis program which managed to divert 47 million tonnes of industrial waste from landfill, while generating £1 billion in new sales and reducing GHG emissions by 42 million tons (NISP, 2014). The program cut business costs by £1 billion through reducing disposal, storage, transport and purchasing costs; it reused 1.8 million tonnes of hazardous waste; and created or safeguarded over 10,000 jobs, while saving 60 million tons of virgin material and 73 million tons of industrial water (International Synergies). In Switzerland, one of the early pioneers of Industrial Ecology, Suren Erkman, created the company SOFIES (Solutions for Industrial Ecosystems) with three former students. Since opening in 2008, it now has more than twenty collaborators, with offices in Geneva, Zurich, Paris and Bangalore. SOFIES is one of the first of a growing number of IE consulting and services company working globally. Another example is a company founded by Australian industrial ecologist Biji Kurup which recently opened offices in India.

Work in Industrial Ecology is on the increase in many parts of the world. A rich variety of activities are being undertaken, as is evident from the overview of research funding above. Highlights of activities in three countries – **Germany,** China and Mexico – provide further evidence of rapid upswing in IE. The first Professor of Industrial Ecology at a German university, Susanne Hartard, was inaugurated in 2009 at the Environmental Campus Birkenfeld. Subsequently, a Masters Program in International Material Flow Management has been established, as well as six courses in IE, including IE and LCA, principles of sustainable business, environmental business economics, and eco-industrial networks. Students also have the option of traveling internationally taking a dual degree with the Japan Asian Pacific University.

In the past few years three programs in IE have started in **China** – at Shandong University, Northeast University and Beijing University of Science and Technology. The Chinese Ministry of Education has also approved a new Bachelor degree in "Resource Recycling Science and Engineering" which has opened at Tsinghua University, Nankai University and China East University of Science and Technology among others. The IE program at Shandong University is a four–year bachelors program; it is now headed by Ronald Wennersten, the former head of the Department of Industrial Ecology at KTH (Royal Institute of Technology) in Sweden.

IE research activities are also growing in China. In 2000, Tsinghua University established the Center of Industrial Ecology, the first institute of industrial ecology in China, and took the leading role in eco-industrial park projects, circular economy planning projects and formulation of the China Circular Economy Promotion Law. In December 2011, Northeastern University of China established the "Institute of Industrial Ecology", which is under the leadership of the "State Environmental Protection Key Laboratory of Eco-Industry". Meanwhile at Shandong University, there is a strong focus on applying IE to urban development. Current research projects include: development of a low carbon eco-city in the Jiangbei Area in Nanjing; a resource-environment oriented study on urban renovation for the inner city of Xuzhou in Jiangsu Province; and a study on the development of a green campus

The work of several industrial ecologists on UNEP's International Resource Panel demonstrates how IE is rising to address global environmental and economic challenges.

at Shandong Jiaotong University. IE researchers at Shandong University are also developing a new applied energy laboratory to study sustainable energy solutions for apartments, houses and office buildings. The aim is to promote an energy transition towards a cleaner energy mix, including various distributed energy sources and energy carriers, as well as towards more resilient and sustainable energy systems.

There is similarly a growing wave of activity in Industrial Ecology in **Mexico**. In August 2010, the Mexican Industrial Ecology Network was created with members from industry and academia in six states. Co-ordinated by Gemma Cervantes, the network convened several course in 2011–2012; and a first Mexican "Diplomate" in IE in 2013. Since 2007, IE courses have been introduced in five universities: Instituto Politécnico Naciona, Universidad Autónoma Metropolitana, Universidad Autónoma de Querétaro, Universidad de Guanajuato, and Universidad Tecnológica de León. The first IE book in Spanish: "Ecologìa Industrial en México" was published in 2013. The Mexican government has also started to develop policies based on principle of IE, the first on industrial symbiosis (2013). Applied research projects are being conducted in several industrial areas including Tampico and Leon.

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APPENDIX

TEN-YEAR MEMBERS OF THE INTERNATIONAL SOCIETY FOR INDUSTRIAL ECOLOGY (as of 2013)

Frederick W. Allen, *U.S. Environmental Protection Agency*

Braden Allenby, *Arizona State University*

Julian Allwood, *University of Cambridge*

Clinton J. Andrews, *Rutgers University*

Robert Anex, *University of Wisconsin Madison*

Midori Aoyagi-Usui, *National Institute Environmental Studies*

Weslynne Ashton, *Illinois Institute of Technology*

Jesse Ausubel, *The Rockefeller University*

Xuemei Bai, *Australian National University*

John Barrett, *University of York*

Diana Bauer, *U.S. Environmental Protection Agency*

Joule Bergerson, *University of Calgary*

Claudia Binder, *University of Zurich*

Rolf Andre Bohne, *NTNU Norwegian University of Science & Technology*

Helge Brattebø, *NTNU Norwegian University of Science & Technology*

J. Alan Brewster, *Yale University*

Stefan Bringezu, *Wuppertal Institute*

Michael Brown, *Brown & Wilmanns Environmental LLC*

Armando Caldeira-pires, *University of Brasilia*

Tracy Casavant, *Eco-Industrial Solutions Ltd.*

Marian Chertow, *Yale University*

Anthony Shun Fung Chiu, *De La Salle University*

Roland Clift, *University of Surrey*

Dwight Collins, *Colbridge And Company*

Timothy Considine, *University of Wyoming*

John Crittenden, *Georgia Institute of Technology*

Benoit Cushman Roisin, *Dartmouth College*

Luiz Fernando Cybis, *Instituto De Pesquisas Hidraulicas*

Mak Dehejia, *Alliance for Sustainable Industry & Energy, LLC*

Gerard Dijkema, *Technische Universiteit Delft*

Faye Duchin, *Rensselaer Polytechnic Inst*

Patrick Eagan, *University Of Wisconsin–Madison*

James Eflin, *Ball State University*

John Ehrenfeld

Mats Eklund, *Linkoping University*

William Ellis, *Northeast Utilities*

Suren Erkman, *Institute for Communication & Analysis of Science & Technology*

James Fava, *Five Winds International*

Paulo Ferrao, *Instituto Superior Tecnico*

Marina Fischer-Kowalski, *Alpen Adria University*

Colin Francis, *The Petroleum Institute*

Fausto Freire, *University of Coimbra*

Uwe Fritsche, *International Institute for Sustainability Analysis and Strategy*

Robert Frosch, *Harvard University*

Tsuyoshi Fujita, *National Institute Environmental Studies*

Sergio Galeano, *Georgia Pacific*

Theo Geerken, *VITO*

Roland Geyer, *University of California–Santa Barbara*

Stefan Goessling-Reisemann, *University of Bremen*

Edward Gordon, *Yale University*

Nancy Gordon

Naohiro Goto, *Toyohashi University of Technology*

Thomas Graedel, *Yale University*

Timothy Gutowski, *Massachusetts Institute of Technology*

Keisuke Hanaki, *University of Tokyo*

Ermelinda Harper, *Yale University*

Seiji Hashimoto, *Ritsumeikan University*

Michael Hauschild, *Technical University of Denmark*

Chris Hendrickson, *Carnegie Mellon University*

John E. Hermansen, *NTNU Norwegian University of Science and Technology*

Allen Hershkowitz, *Natural Resources Defense Council*

Edgar Hertwich, *NTNU Norwegian University of Science and Technology*

Anne Hewes, *Ecomaine*

Masahiko Hirao, *University of Tokyo*

John Holmberg, *Chalmers University of Technology*

Gjalt Huppes, *University of Leiden*

Jacqueline Isaacs, *Northeastern University*

D. Jacobs *Rochester, Institute of Technology*

Ravi Jain, *University of The Pacific*

Jeremiah Johnson, *University of Michigan*

Somporn Kamolsiripichaiporn, *Chulalongkorn University*

Barbara Karn, *U.S. Environmental Protection Agency*

Christopher Kennedy, *University of Toronto*

Gregory Keoleian, *University of Michigan*

Rene Kleijn, *Leiden University*

Dinah Koehler, *U.S. Environmental Protection Agency*

Yasushi Kondo, *Waseda University*

Fridolin Krausmann, *Institute for Social Ecology*

John Paul Kusz, *Illinois Institute of Technology*

Peter Laybourn, *National Industrial Symbiosis Programme*

Pascal Lesage, *Polytechnique Montreal*

Stephen Levine, *Tufts University*

Reid Lifset, *Yale University*

Peter Lowitt, *Devens Enterprise Commission*

Patrick Mahoney *Energy Answers LLC*

Eric Masanet *Lawrence Berkeley Labs*

Tohru Matsumoto *Kitakyushu University*

Deanna Matthews *Carnegie–Mellon University*

Sarah McLaren *Massey University*

Ottar Michelsen *NTNU Norwegian University of Science & Technology*

Andreas Moeller *Leuphana University of Lueneburg*

Henri Moll *University of Groningen*

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Arnold Tukker *TNO Built Environment & Geosciences*

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Ester Van Der Voet *Leiden University*

Bruce Vigon *Society of Environmental Toxicology & Chemistry (SETAC)*

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