

International Society for Ecological Economics Online Encyclopaedia of Ecological Economics

Industrial Ecology

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1. Introduction

Industrial Ecology is a young field, with intellectual roots in engineering and management. It is mainly concerned with tracking flows and stocks of substances and materials, especially those whose cycles are heavily influenced by industrial activities, as a basis for reducing the impact of the production process on the environment. The field was officially created at a meeting at the National Academy of Engineering in 1992 with support from the AT&T Foundation, and the latter (now the Lucent Foundation) has sponsored annual Industrial Ecology Faculty Fellowships ever since. The first issue of the *Journal for Industrial Ecology* appeared in 1997. Gordon Research Conferences in Industrial Ecology have taken place every other year since the first one in 1998. The International Society for Industrial Ecology was announced in 2001. The first International Conference in Industrial Ecology (ISIE) was held in Leiden, the Netherlands, in the same year and the second in Ann Arbor, Michigan, in 2003. Histories of the field have been written (O'Rourke et al. 1996; Erkman 1997; Fischer-Kowalski 1999; Fischer-Kowalski and Hüttler 1999), and a growing number of university departments offer courses directly related to Industrial Ecology although there are at the present time only two degree-granting programs with this name (at Mount Royal College in Canada and the Norwegian University of Science and Technology).

Many of the concerns and methods of Industrial Ecology overlap with those of Ecological Economics, and not surprisingly a growing number of researchers identify with both fields. As a highly interdisciplinary field in the process of inventing and defining itself, Industrial Ecology has a diverse membership with varied interests, and any overview will inevitably reflect the knowledge and perspective of the authors. While recognizing these limitations, this entry sets out to describe the current status of Industrial Ecology and to identify directions that are likely to take on increasing importance in the future.

2. What is Industrial Ecology?

The name "industrial ecology" emerged independently in several places. Probably the first use of the term was by Japanese research and planning groups studying how to reduce their country's dependence on resources (Watanabe 1972). The term was next used in the title of a Belgian study of

national energy and material flows (Billen et al. 1983) and in a manual on cleaner production and material cycling by a German industrialist (Winter 1988). Industrial Ecology was introduced in the English-speaking world through an article by Robert Frosch and Nicholas Gallopoulos, "Strategies for Manufacturing" (1989), that appeared in a special issue of *Scientific American* devoted to Managing Planet Earth. This article was widely read and can be said to have launched the field. The authors argued that environmental constraints require new ways of thinking about industrial production. According to the old conception, the production process absorbs inputs from the environment, transforms them into both useful products and wastes, and then discharges the wastes. However, current levels of population and affluence have put substantial pressures on the environment. Even more worrisome for the environment, according to this argument, is the fact that the populations of the developing countries are still growing and have every reason to aspire to the material standards of living of the rich countries. In order to meet these future demands without unacceptable environmental damage, the authors concluded that decision makers in industry need to "mimic" in their production facilities the operation of ecosystems in nature that generate no wastes because of intricate channels for reusing residuals.

Frosch and Gallopoulos's persuasive formulation of Industrial Ecology provided the name for a body of work that had begun decades earlier. Particularly central to the new field were the ideas of Robert Ayres, which, using a related but different biological metaphor, he had come to call "industrial metabolism" (Kneese, Ayres and D'Arge 1970; Ayres 1989). The metabolism of the industrial system would be described through detailed "material balances," which could be compiled for a production unit, such as a factory, or a geographic unit as small as a village or as large as a continent. This approach quantifies the amount of a substance, such as chlorine or lead, entering the boundary of the unit in question from all sources outside that boundary and describes the fate of the substance in terms of the amounts embodied in product and the amounts dispersed as waste in various reservoirs at all stages of production and use. The underlying principle for constructing the balances is the conservation of mass. Data are taken from both published and proprietary sources, with the reconciliation of balancing what goes in with what goes out reliant on an engineer's specialized knowledge of production processes and reservoirs.

While Industrial Ecology represents many points of view and many types of contributions, nonetheless variants of material balances, namely substance flow analysis and material flow analysis, provide the unifying conceptual and methodological core for Industrial Ecology. Material flows include everything from single elements, such as chlorine, up to mass flows measured in composite tons. As is evident from the focus on industry that is explicit in its name (and in "industrial metabolism," too, for that matter), the compilation of material balances is intended mainly to provide decision support for industrial managers and engineers. It is also directed at government agencies with policy responsibility for environmental protection.

A distinguishing objective of Industrial Ecology is to influence industrial decision making. The concepts of closing production loops, networks and food-webs, and bio-mimicry inform the design of eco-industrial parks (Chertow 1998; Indigo Development 2003) and, more generally, design-for-the-

environment procedures for use in industrial settings. The latter generally employ a suite of checklists and related tools to assist in product design and implementation (Graedel and Allenby 1995; Winter 1988). An early and widely read document intended for this audience is the brochure by Tibbs (1991), entitled "Industrial Ecology: An Environmental Agenda for Industry," that enjoyed wide distribution first from A.D. Little and then from the Global Business Network. Today, environmental considerations have been incorporated into many routine corporate decision-support tools and management information systems. More comprehensive analyses take the form of material balances conducted for a facility or life-cycle assessments of products to help managers identify problem areas and evaluate processing trade-offs.

While the micro level of Industrial Ecology is comprised of physical balances for a growing number of materials and spatial units, the macro level is concerned with the formulation and evaluation of options for key decision makers. As in many other fields, there are substantial challenges in achieving conceptual and operational linkages between the micro and macro levels. An attempt to bridge this gap takes the form of an intermediate, or meso, level of analysis that is represented by the substantial bodies of work in life cycle analysis and input-output economics and, in particular, by the growing linkages between them.

2.1. Material Flows, Energy Flows, and Environmental Accounting

Substance flow analyses have been carried out for many metals, especially those that are considered to pose threats to human health such as lead or mercury. Highly detailed studies of this kind include a collection of articles in the *Ecological Economics* journal tracing stocks and flows of copper by Graedel and colleagues (Graedel 2002). Another focus of attention is the geographic region, such as the Rhine Valley (Stigliani et al. 1993).

Societal metabolism is a generalization of the concept of industrial metabolism to an entire socioeconomic system, which is described by the extent of its reliance on the physical environment. Often the material flows are aggregated with the composite mass measured in tons (Fischer-Kowalski and Hüttler 1999; Matthews et al. 2000). Analogously, composite energy balances compiled in joules (Haberl 2001) have been developed for past and present societies and used to distinguish societies with different types of production systems, notably hunter-gatherer, agricultural, and industrial. Researchers are also engaged in compiling data to describe the use of time by inhabitants of different societies. The underlying idea is that one may be able to identify transitions from one type of societal metabolism to another by tracking these material and time measures or to distinguish alternative forms of industrial and post-industrial systems of societal organization.

Even if we restrict the geographic focus to the national level, the compilation of material and energy balances, whether for individual substances, materials, or highly aggregated composites, poses many challenges. Some of these challenges are familiar to national statistical offices from their long experience with economic accounts while others are entirely new and still being addressed. Starting in the 1980's, efforts began to "green" the System of National Income and Product Accounts by supplementing what had been an economic database almost exclusively in money units. A variety

of approaches were explored for compiling “satellite” natural resource accounts. For some the objective was to arrive at a single figure to “adjust” Gross National Product – itself a single figure -- for resource depletion and environmental degradation. Others aimed at developing a detailed database about resource use and waste generation that could be used for multiple purposes. In 1993 the United Nations published guidelines for a System of National Environmental and Economic Accounts intended to systematize for statistical offices around the world the detailed accounting for material and energy flows in physical units like tons and joules.

The compilation of such accounts requires a system of classifications, conventions and definitions to guide individual data collection efforts and assure the compatibility of different parts of a given national database and rough comparability among different economies described in this way. Various classification schemes have been developed for environmental accounts and time use, but they do not yet possess the maturity and stability of the Standard Industrial Classification that governs the collection and analysis of economic data about production. Nonetheless, collection of data on resource use and wastes is an area of expansive activity in statistical offices, and the distinctions between “green accounting” and material balances is being blurred, with definitions and conventions being devised as experience with these data mounts.

In the economic accounts, conventions guide such matters as the treatment of secondary products. An important convention in the material flow accounts is that the only water flow recorded is process water, as the large volumes of water required for cooling would otherwise dwarf other material inputs. Conventions for the energy balances require the inclusion of food for draft animals as an energy input by contrast with the more restricted definition of energy sources that has been dominant in national statistics until now.

Data on material flows are also collected and organized in the form of the familiar input-output table, in this case called a physical input-output table or PIOT (Stahmer et al. 1998). Each entry of the PIOT measures the flows from one industry to another measured in tons rather than the money units used in economic input-output tables. Developing figures for a PIOT is based on the conservation of mass, with mass in to any sector equal to mass out. This principle parallels the balance concept of the economic input-output table, which is based on the fact that the cost of each sector’s inputs (including profits) equals the money value of its output.

The compilation of PIOTs benefits from the experience with economic input-output tables with regard to concepts and practices to assure that a particular flow is not counted more than once as substance, as material embodied in commodities, and as final product. This is parallel to the additivity of factor payments or of final deliveries in economic accounts (each of which adds to gross national product) so long as one does not attempt to add gross output of different sectors (which would involve “double-counting”). A number of research teams are engaged in this work, notably the Institut für Interdisziplinäre Forschung und Fortbildung of the Austrian Universities. From the point of view of an economist, a table in mixed units, such as tons, joules, and cubic meters, would be more useful for both description and analysis.

The kind of data work that has been described above provides a snapshot of the state of the interaction between the socioeconomic system

and the environment at the present time or for the past. These data are valuable to monitor progress: as a general rule, less discharge to the environment is better than more, and with some consensus on weightings, summary indicators can be devised to serve as a report card or indicate to government and corporate decision makers where there are opportunities for improvement. However, other concepts and other kinds of information are needed as a basis for developing actionable strategies for the future. Accordingly, other researchers within the field of Industrial Ecology are engaged in posing questions for which the answers rely only in part on information regarding the past and present use of materials and the associated generation of wastes.

2.2. The Product Level: Life Cycle Analysis

Life cycle analysis is the area that accounts for the largest number of articles in the *Journal of Industrial Ecology* and the most sessions at professional meetings. With its origins in engineering and much of its practice associated with industrial consulting, life cycle analysis (LCA) has as its objective quantifying the environmental burden imposed by an industrial product or process. This involves measuring or estimating the material and energy inputs and releases to the environment associated with the product at all stages from the extraction and processing of inputs through the use and eventual disposal of the product. The principal professional society for LCA is the Society for Environmental Toxicology and Chemistry (SETAC) (Consoli et al. 1993). The International Society for Industrial Ecology has also become a professional home for this kind of work, with its ties both to materials and energy use on the one hand and to decision-making processes on the other. Joint symposia have been organized by SETAC and the International Society for Industrial Ecology in recent years.

The LCA community has developed classifications, conventions and definitions, standards, shared software and shared databases for carrying out its work both in research settings and through consulting to industry and governments, clients who require standardization of assumptions and methods. To achieve this, the LCA community has worked closely with the International Organization for Standardization (ISO), a network of worldwide institutions that develops common technical specifications, to produce standards (such as ISO14040 to 14047) that define LCA, including environmental management standards like one on environmental labels and claims (ISO 14023). Thus defined, the standard practice of LCA includes four steps: definition of the goal and scope of a project, inventory analysis to identify and quantify inputs and outputs at every stage of the life cycle, assessment of the impact of these inputs and outputs, and interpretation of the significance of impacts (Guinée et al. 2002). Despite this high degree of formal standardization, there is still a great deal of discretion in decisions regarding the modeling of the input inventory and the impact assessment. A recently launched collaboration between SETAC and the United Nations Environment Programme (UNEP) is the UNEP/SETAC Life Cycle Initiative⁽²⁰⁰³⁾ intended to further develop life cycle analysis and expand its use.

A life cycle analysis aims to characterize the environmental impact of actual or hypothetical products as a basis for comparing them. It quantifies the environmental stressors, such as emissions and resource use, associated

with a "functional unit" of product, such as the washing of 1000 kg of clothes or the packaging and delivery of 1 million individual portions of a soft drink. An LCA is commonly conducted on the basis of average process characteristics (rather than marginal ones) and hence assumes a set of linear relations between amount of product and impact. The inventory modeling of some LCA software tools uses input-output analysis (e.g., Frischknecht et al. 1996; Heijungs 1994), which shares these assumptions.

Fundamental challenges faced in an LCA are delimiting the system's boundary for the particular product and identifying all environmentally significant production processes. It has been estimated that process chain analysis, which identifies direct inputs and outputs only, accounts for about half of the product's impact, while the other half is distributed among a large number of individually insignificant upstream processes (Lave et al. 1995; Lenzen 2001). Economic input-output tables and the mathematics of the static input-output model are used in so-called hybrid LCA to quantify the numerically important indirect portion of the impact (Suh and Huppes 2000).

The challenge in the impact assessment step is to evaluate the significance of hundreds of inventory items in terms of a small number of indicators (Hertwich et al. 1997). Environmental stressors may be aggregated to impact categories such as climate change, ozone depletion, human toxicity, ecosystem toxicity, and biotic resource depletion. Alternatively, impact can be reported in terms of damage categories, like years of life lost due to cancer or an estimate of the monetary cost of damage (Steen and Ryding 1991).

An extensive literature reflects a lively debate on methodological issues, including how to deal with the fact that choices among products are ultimately value-laden (Hertwich et al. 2000; Udo de Haes et al. 2002). As in the case of economic cost-benefit analyses, a large number of assumptions are made but generally not explicitly stated. However, unlike a cost-benefit analysis, LCA results are usually not reduced to a single figure. Thus a judgmental comparison of trade-offs is explicitly required. This is true of well-known product comparisons like cloth vs. disposable diapers or paper vs. polystyrene cups (Lave et al. 1995). However, the value judgments required to evaluate trade-offs are even greater when the options have broader societal significance. A good example is comparing the merits of using vacant agricultural land for producing organic food or biomass for energy (van den Broek et al. 2001).

2.3. The Meso-Level: Input-Output Economics

Input-output economics is the study of the interdependence of the different parts of an economic system. This approach to describing and analyzing an economy was launched by Wassily Leontief with the publication of a pair of articles in the 1930's. While the International Input-Output Association was created only in 1988 and its journal, *Economic Systems Research*, dates to 1989, the community has been holding international conferences since 1950. Today statistical offices around the world compile and publish input-output tables and related data on a regular basis as a central part of their national accounts.

The input-output table, derived from economic censuses and surveys, describes all economic transactions in an economy with an especially detailed focus on inter-industry purchases and sales. It is converted by a simple

manipulation to a matrix of inputs per unit of output, which serve as structural parameters. This is a crucial step because it permits the passage from description and descriptive statistics to modeling of alternative scenarios. The matrix and other related data are manipulated in a model that, in its simplest static form, is a system of balance equations involving the matrix inverse, sometimes called the Leontief inverse. An individual balance equation in the physical input-output model assures that those outputs of a sector distributed to other sectors and those going to consumers add up to total production. Corresponding to the physical model is a price model: a balance equation in the price model assures that the costs of individual inputs to production plus profits add up to the unit price. The equations are solved for total (direct plus indirect) production requirements to satisfy given deliveries to consumers and for the vector of prices (or price deflators in the common case where the variables in the physical model are measured in money units) that covers both intermediate inputs and costs of factors of production.

A column in an input-output matrix is a compact representation of the direct inputs to production for a given sector. The corresponding column of the inverse matrix captures the indirect inputs from all other sectors as well as the direct ones. It is this feature which is of special interest for life cycle analyses (see above). The use of input-output models to track the use of materials and energy, the generation of waste and the possible reuse of waste are described in several articles by Duchin that also demonstrate the representation of alternative technological assumptions as changes in columns of input-output coefficients (1990, 1992, 1994).

While the input-output table and the static physical input-output model have been used successfully and extensively in LCAs, input-output economists also make use of a variety of conceptual extensions including the static price model (mentioned earlier), dynamic physical and price models, and optimization models that select low-cost technologies. These models are used with data collected in a variety of ways to explore not only the impact of actual or hypothetical products and processes but also to evaluate the implications of moderately detailed scenarios about the future. Studies with direct relevance for Industrial Ecology include the investigation of carbon emissions (Proops, Faber and Wagenhals 1993), an evaluation of the recommendations of the Brundtland Report (Duchin and Lange 1994), the recycling of plastics (Duchin and Lange 1998), waste management (Nakamura and Kondo 2002), and water use (Duarte, Sánchez-Chóliz, and Bielsa 2002).

Alternative scenarios about the future play a role in input-output analysis that is similar to that of alternative actual or hypothetical products and processes in an LCA study, and collaboration between these communities is now established and poised to expand. Recently a joint Working Group between the International Society for Industrial Ecology and SETAC was created on Input-Output Analysis in Life Cycle Assessment. One area where collaboration may prove especially fruitful is in bringing household lifestyles and consumption into the purview of Industrial Ecology. There is a substantial and growing body of research on this subject (Herendeen and Tanaka 1976; Duchin 1998; Wier et al. 2001), and Hertwich maintains a website on new developments (Hertwich 2003).

3. Relation of Industrial Ecology to Ecological Economics

The fields of Industrial Ecology and Ecological Economics are both issue-oriented, and both take a systems approach to understanding and resolving challenges to the physical environment. There is a substantial overlap of concerns between the fields and, not surprisingly, an overlap also in their membership. Both fields are concerned with flows of substances, materials, energy, water, and wastes through an economy and with footprints, rucksacks, and other big-picture indicators of environmental health (see, for example, Cleveland 1999).

Ecology figures in the names of both fields. In Industrial Ecology, this is a metaphor calling attention to closing of loops and mimicking nature. Ecological Economics is more literally named. In many ways the conception of ecology as a systems approach based on interdependency plays the role of theory in both fields. Industrial Ecology is based in engineering: most of the founders are or were engineers or applied physicists in university or corporate settings. Ecological Economics has its roots in economics and ecology. Both fields struggle to create a distinctive yet manageable approach to a vast substantive scope that includes many aspects of both the natural world and society.

Ecological Economics is focused on economic questions and methods, especially valuations, notably estimates of costs and benefits, and economic development, including attention to economic concepts like savings and investment dynamics and the distribution of income. It is also focused on ecology, including biodiversity and approaches to the management of specific ecosystems. It makes more extensive use of mathematical models of an economy, especially input-output models and general equilibrium models, and also continues to debate the weaknesses and strengths of neoclassical economics.

While both make use of input-output economics, Ecological Economics focuses more on modeling while Industrial Ecology, at least until now, has been more active in data development. There is a body of research applying input-output models to ecosystems that may well turn out to be an additional unifying link between the two fields (Hannon 1973; Patten 1981).

Industrial Ecology is mainly concerned with managers as decision makers in a manufacturing setting in an industrialized economy. It focuses on material flows or industrial metabolism and attempts to move from there in a systematic way to the societal level. Revealing its roots in engineering, it pays greater attention than Ecological Economics to the detailed identification and quantification of sources and sinks of substances and materials in a given economy, especially those that are substantially affected by human activities. For the same reason it benefits from a long history of standards for data and analysis and is now making a major effort to create standards for national statistical offices and individual researchers collecting physical input-output data. There is no corresponding consensus within Ecological Economics as to the central role of a common body of data. Some members of the Industrial Ecology community desire to maintain the focus on improving and expanding the materials databases while others put priority on analysis and using the requirements of the analysis of scenarios to determine priorities for the collection of data.

4. Conclusions

The strength of Industrial Ecology lies in description of the material world. There are large bodies of scholarly and proprietary literature describing material and energy flows as well as chemical emissions on different spatial levels from individual industrial processes at a single site to the global setting. Industrial Ecology uses ecology as a metaphor to inform corporate and to a lesser extent policy-level decision making. Industrial Ecology has begun to use mathematical models both to improve description and also to analyze scenarios about the future.

Industrial Ecology aims to provide information for decision makers, especially in a corporate setting, but also in public institutions and households. It has until now not embraced systematic approach to studying the economic, social and psychological aspects of decision making. These areas are outside the paradigm of Industrial Ecology since they are not traditionally an area of expertise of engineers and natural scientists. While Industrial Ecology is a truly interdisciplinary enterprise, the concerns of social scientists are addressed only on its margins. This fact is of fundamental importance for identifying areas for fruitful collaboration between Industrial Ecologists and Ecological Economists.

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