

Industrial Ecology: Policy Potential and Research Needs[†]

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ABSTRACT

Over the past decade, a new approach to environmental analysis has developed. Although the scope and definition are not yet completely fixed, the new field of “industrial ecology” focuses on reducing the environmental impacts of goods and services, on systems-based analysis of environmental problems, and on innovations that can significantly improve environmental performance. Industrial ecology has significant potential for U.S. environmental policy. But to establish a firm foundation for significant policy initiatives, there is a need for better understanding of the potential and limitations of a range of promising ap-

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proaches including: (a) technological innovation, (b) voluntary and cooperative approaches to environmental management, (c) substitution of services for products, (d) recycling and reuse, (e) reduction in the amounts of materials used in products, and (f) substitution of scarce resources with those that are plentiful.

Key words: industrial ecology; innovation; environmental policy; dematerialization; life-cycle assessment (LCA); materials flows analysis (MFA)

INDUSTRIAL ECOLOGY

OVER THE PAST DECADE, a new approach to environmental analysis has developed. Although the scope and definition are not yet completely fixed, the new field of “industrial ecology” focuses on reducing the environmental impacts of goods and services, on systems-based analysis of environmental problems and on innovations that can significantly improve environmental performance. The scope of industrial ecology includes the entire life cycle of products and services, drawing on and extending a variety of related approaches including systems analysis, materials flow analysis, pollution prevention, design for environment, product stewardship, energy technology assessment, and eco-industrial parks (Ausubel and Sladovich, 1989; Jelinski *et al.*, 1992; Allenby and Richards, 1994; Socolow *et al.*, 1994; Graedel and Allenby, 1995; Allenby, 1999; Kates *et al.* 2001; Lifset and Graedel, 2002; Seager and Theis, 2002). A report from the National Academy of Sciences identifies this area as one of the eight Grand Challenges of Environmental Science (National Academy of Sciences, 2001).

Industrial ecology emphasizes innovation. It emphasizes the opportunities for new technologies and new processes, and the opportunities for economically beneficial efficiencies. It provides a long-term perspective, encouraging consideration of the overall development of both technologies and policies for sustainable resource utilization and environmental protection into the future.

Through the use of systems-oriented tools such as materials flow analysis (MFA) and life-cycle assessment (LCA), industrial ecology can complement and enhance the single-pollutant risk-based framework of traditional environmental policy (Powers and Chertow 1997). It could help environmental policymakers address some of the core challenges of environmental policy, from climate change to waste management to land use policy.

1. Climate Change: technological innovation will be key to any number of approaches to climate change, from renewable energy technologies to energy efficiency to carbon sequestration.

2. Waste Management: innovations in industrial systems and processes have the potential not only to reduce wastes, but also to make the remaining wastes more economically useful and environmentally benign. With insights gained from industrial ecology, the nation’s waste management program (RCRA, the Resources Conservation and Recovery Act) could be redesigned as an innovative program that actually fits its name: to conserve and recover resources through closing loops in the lifecycle of materials and minimizing material use (Fagan *et al.*, 2000).
3. Land Use and Urban Areas: the interconnected issues of land use policy, transportation systems, urban air quality, and economic and technological infrastructure require a long-term strategic approach to environmental policy. Industrial ecology seeks to address not just industrial emissions, and not just specific products, but the complex networks of services, products, and activities that make up our economy (Stern *et al.* 1997; Bugliarello, 2000).

We believe that industrial ecology offers significant potential for U.S. environmental policy. However, the field of industrial ecology is still sorting out which of its ideas, assumptions, and approaches are most likely to provide significant environmental benefits. Thus, we advocate a near-term research effort to strengthen and assess the tools and assumptions of industrial ecology. The research needs identified here are not intended to be a comprehensive research agenda for industrial ecology, but rather an agenda focused on testing and strengthening the core assumptions and approaches of the field. Several more general research agendas have been developed, including agendas developed by Wernick and Ausubel (1997), Vellinga and Herb (1999), Gutowski and Murphy (2001), and Thomas and Graedel (2002).

In the following sections we discuss related policy developments, research to examine the fundamental assumptions of industrial ecology, and research to improve some of the main applied tools of industrial ecology.

POLICY APPLICATIONS OF INDUSTRIAL ECOLOGY

Historically, U.S. environmental regulation of industry has emphasized point source controls, especially of gaseous, liquid, and solid emissions from manufacturing plants. In the past few years, the U.S. EPA has initiated a number of innovative policies of the industrial ecology type (U.S. EPA, 2001). Elsewhere in the developed world, however, these new approaches have been adopted more quickly and more fully. In Europe, environmental policies increasingly address the overall environmental impacts of a product over its entire life cycle (raw materials extraction, product manufacturing, product use, and disposal or recycling). One example is the European Union's proposed Integrated Product Policy (IPP), which seeks to stimulate demand for greener products and to promote greener design and production (Commission of the European Communities, 2001). In Japan, the emerging emphasis is on the environmental design of products, driven both by concern over scarce resources and by business strategy. The emphasis is on extensive recycling of products and environmental attributes such as energy efficiency and use of nontoxic materials (National Academy of Engineering, 1994; Life Cycle Assessment Society of Japan, 1998; Gutowski and Murphy, 2001).

In Europe and Japan, increasing attention is being paid to materials flow analysis as a means of assessing resource efficacy and sustainability (Matthews *et al.*, 2000). Materials flow analysis, the calculation of flows of materials from cradle to grave, is being used to complement risk analysis and to provide insight into the challenges of sustainable use of resources (Van der Voet, 2000; Bringezu and Moriguichi 2002).

These developments signal an international shift in emphasis from managing individual manufacturing wastes and emissions to managing the overall environmental impacts of industrial sectors and of products over their life cycles. In response, global industrial firms, participating in commerce in the United States, Europe, and Japan, are beginning to apply these concepts to their products, manufacturing processes, and environmental programs.

These developments pose opportunities for and challenges to U.S. policy. They challenge U.S. policy both because there is the possibility of inconsistent regulatory obligations across national borders, and because the analytical and policy framework is different from the traditional U.S. approach. The growing diversity of environmental policies for products could raise trade issues; on-going activities in the European Union and other countries could place the United States in a reactive mode.

U.S. policy adaptations of industrial ecology might be

different from the approaches that have been taken in Europe and Japan. With its often litigious and adversarial approach to environmental policy, the United States has developed an emphasis on quantification of environmental risks and on the scientific evaluation of environmental policy. This emphasis is likely to be reflected in U.S. policy adaptations of industrial ecology as well. Moreover, as the importance of both information technology and the technological infrastructure are increasingly recognized, application of industrial ecology may progress from its initial emphasis on specific products and materials to a broader emphasis on infrastructure and technological systems and resource efficiency.

FUNDAMENTAL ASSUMPTIONS OF INDUSTRIAL ECOLOGY

If industrial ecology is to provide a basis for environmental policy, it needs a well-developed scientific foundation. In the same way that fundamental scientific research supports technological development, and fundamental economic research supports the development of both economic policy and the economic system, fundamental research in industrial ecology is needed to provide a robust framework for understanding the interaction of technologic systems and environmental protection. In particular, theories need to be stated explicitly, tested against real data, and their limitations and range of applicability need to be established.

Fundamental research in industrial ecology focuses on the long-term relationships between materials and energy use, the environment and human health, and economic well-being. The examples below focus on materials and energy efficiency and substitution, the role of innovation, and the role of the private sector. The emphasis is on economy-wide consumption of materials and energy, and on how this will change in the future. Concern over resource use includes consideration of environmental impacts and ecosystem services as well as the narrower issue of resource availability and longevity (Ayres, 1993; Daily, 1997).

Materials and energy efficiency and substitution

Since the 1970s a growing body of research has suggested that greater material efficiency, use of better materials, and the growth of the service economy are contributing to the "dematerialization" of the economy. Yet the extent of this phenomenon remains unclear. Simon's (1980) analysis of worldwide trends in natural resource use and the environment has been widely criticized as overly optimistic (Holdren *et al.*, 1980). Undertaking a more limited analysis, Larson, Ross, and Williams (1986;

Williams *et al.*, 1987) argued that economic growth in developed countries is no longer accompanied by increased consumption of basic materials. This dematerialization has been investigated for a range of materials, including steel, plastics, paper, cement, and a number of metals.

Despite these promising results, neither the extent of dematerialization nor its implications are yet understood. Wernick *et al.* (1996) pointed out that some products, such as personal computers and beverage cans, have become lighter over the years, but use of other materials, such as paper, have increased. Although primary materials use is not rising as fast as economic productivity, there are no signs of net dematerialization among consumers or of saturation of individual material wants. In a review of the dematerialization literature, Cleveland and Ruth (1998) argued that understanding of the patterns of material use are limited largely to individual materials or specific industries.

A related body of research suggests that expensive, scarce, or environmentally harmful resources can be substituted by resources that are cheap, abundant, and environmentally benign. For example, Goeller and Weinberg (1976) used a geologic and chemical analysis to argue that, with the important exception of fossil fuels, the use of scarce minerals can be substituted with other minerals that are essentially inexhaustible. Their analysis countered the "Limits to Growth" report, which had argued that growing consumption would inevitably deplete basic materials (Meadows *et al.*, 1972). "Substitution" can be seen in the changes in energy sources that have occurred over the past century. As the sources of energy have shifted from wood and coal to petroleum, nuclear energy, and natural gas, the average amount of carbon per unit energy produced has fallen, resulting in a "decarbonization" of world energy use (Nakicenovic, 1996). Overall, however, the potential for and limitations of substitutability remain unresolved (Tilton, 2002).

It is often suggested that "loop closing"—the recycling and reuse of products, materials, and wastes—has significant environmental potential. Graedel and Allenby (1995) have suggested that the goal of industrial ecology is to accomplish the evolution of manufacturing to a system in which all wastes are recycled. Understanding of the potential to reach this goal, and the environmental risks and benefits, is needed.

One strategy for reducing environmental impacts is the substitution of services for products. The notion is that people seek not physical products, but rather the services provided by those products. By emphasizing the service instead of the physical product, firms would have an incentive to be more efficient with materials and energy. For example, an integrated pest management ser-

vice might provide crop protection rather than selling pesticides *per se*. Product-to-service strategies hold potential for innovative environmental strategies and considerable environmental gain, but they need further conceptual analysis and systematic empirical testing (Stahel, 1994; Ryan and Mont, 2001).

Role of innovation

Other researchers have used biological analogies to suggest that "industrial ecosystems" have vast potential for improved efficiency through innovation and integration (Ayres, 1989). Frosch and Gallopoulos (1989) argued that

the traditional model of industrial activity—in which individual manufacturing processes take in raw materials and generate products to be sold plus waste to be disposed of—should be transformed into a more integrated model: an industrial ecosystem. In such a system, the consumption of energy and materials is optimized, waste generation is minimized, and the effluents of one process—whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products—serve as the raw material for another process.

However, debate remains as to the potential of industrial symbiosis, and the role of ecoindustrial parks in environmental management.

The biological, evolutionary analogy of industrial ecology suggests that the focus of environmental policy should increasingly emphasize innovation. This also suggests an increasing research emphasis on the development of environmentally beneficial technologies. In addition, there is a need for research on the innovation process itself and on the role of government in that process.

The role of the private sector

A number of researchers look to industrial firms to take a leading role in environmental management and policy. There are two dimensions to this premise: (i) optimism that voluntary approaches can be effective in bringing about environmental improvement, and (ii) reliance on industrial firms as the locus of technological expertise, which in turn, is seen as crucial to strategies emphasizing design for environment (DfE).

Industrial firms are clearly a locus of technological expertise. But use of ecodesign by businesses is both partial and uneven (Tukker and Eder, 2002). A more thorough understanding of the factors that influence the adoption of ecodesign is needed. In addition, clarity about what constitutes a green product is needed so that com-

panies that are inclined to use their technological expertise to this end can have confidence that their efforts are well targeted.

It is often argued that cooperative approaches are more cost effective, more conducive to innovation, and better able to promote fundamental attitudinal change than traditional “command and control” regulation. On the other hand, skepticism about the effectiveness of voluntary approaches remains. The claim that there are extensive unexploited win–win opportunities in environmental policy is similarly the subject of active research and debate (Esty and Porter, 1998).

Incentive-based approaches to improved environmental management are also controversial because of debate over which approaches are best for different applications and because of disputes about their policy implications (Tietenberg, 1997; World Resource Institute, 2000).

Better understanding is needed of the potential and limitations of industry’s role and of the specific circumstances that can encourage industry to be environmentally proactive. There is a need to understand what motivates change. There is a need for greater attention to program evaluation, and examination of the effectiveness of the new policy instruments in comparison with traditional regulatory and market-based incentives (O’Rourke *et al.*, 1996; Harrison, 1998; Andrews *et al.*, 2002).

APPLIED TOOLS AND METHODS

Whereas the fundamental research in industrial ecology addresses questions of how the industrial system can evolve to reduce environmental impacts, applied research focuses on the methods and data needed to assess specific products, facilities or industries. The examples below emphasize the need for critical evaluation and peer review of an ensemble of software, databases, and metrics.

Software and databases for life-cycle assessment

A life-cycle assessment (LCA) evaluates the entire environmental impact of a product through its life cycle, including manufacturing, use and disposal. A great deal of work has been done to develop the technical foundations for LCA of products and processes, and to develop the databases necessary to support these assessments. The International Organization for Standardization (ISO) is working to formalize LCA methods. Efforts within the United States to develop LCA methods are being led by the Society for Environmental Toxicology and Chemistry (SETAC) and the U.S. EPA, as well as the American Center for Life-Cycle Assessment (U.S. EPA, 2000).

LCA is the method by which the environmental im-

pacts of different products or activities can be compared on a systematic basis. To apply industrial ecology, it is essential to be able to reliably compare the environmental impacts of different choices of products, activities, or designs.

There are now a large number of competing software packages for LCA and related applications (de Caluwe, 1997). Because of the wide range of tools, it is difficult for users even to determine which tool is best suited to a particular situation. These software tools are often complex, opaque in their technical assumptions, and use data that are difficult to verify (Norris and Yost 2001).

Methods to validate LCA results have yet to be established (Hendrickson *et al.*, 1998). Both conventional peer review of the LCA methods and software, and development of standardized “test-beds” (data sets or protocols) could provide users with increased confidence that actions based on the tools would indeed lead to overall environmental improvements. One of the main issues of LCA has been the validity of available life cycle inventory (LCI) databases, which are the basis for any LCA studies but are neither standardized nor peer-reviewed. There is a need for a comprehensive, national-level LCI database that is open and peer-reviewed, and that contains reliable industrial data. Some efforts to address this need are currently underway; continued support of work in this area is needed (NREL, 2001).

Weighted metrics

Applied industrial ecology aims simultaneously to reduce a range of environmental impacts, including not only the mass of emissions and wastes, but also impacts on human health and ecosystems. To integrate across diverse dimensions of environmental performance, a number of weighted environmental metrics have been developed. For example, a scoring system called eco-indicator is a measure of overall environmental impact; human toxicity potential has been developed as a measure of the toxicity of chemical compounds over a range of human health end points; and the “triple bottom line” is a measure being used by some industrial companies to combine business, environmental, and social accounts (National Academy of Engineering, 1999; Huisman *et al.*, 2001; Luo *et al.*, 2001; Hertwich *et al.* 1997). Some weighted metrics are being considered in the European Union and elsewhere for use in environmental legislation.

The validity and limitations of such weighted metrics need to be clarified. The key questions are the commensurability of the attributes that are being combined, and the validity of the weighting scheme. For example, the toxicity of a chemical is a function of dose, the medium

of exposure, the duration of exposure, the state of the receptor (condition, characteristics, and activity level), the route of exposure and the chemical and physical state of the pollutant. A weighted measure of the toxicity of different compounds must make assumptions about all of these factors, and indiscriminate application of such a metric may lead to nonrepresentative outcomes. Hence, there is a need for deeper understanding of how weighted metrics are developed, of the impacts of uncertainty and variability, and of the limitations and benefits of their application.

Simplifying assumptions

Industrial ecology has generated an ensemble of simplifying assumptions used in calculations and analysis. For example, LCAs are often simplified by assuming that mass is a reasonable proxy for environmental impact, or by only assessing materials that comprise at least 5% of the product mass, or by not including some of the indirect upstream premanufacturing steps related to materials extraction and processing (Curran, 1996; ISO Hertwich *et al.*, 1997; 14041, 1998). Similarly, the aggregate flow of materials in an economy is often used as a first approximation of the sustainability of human activity. The effects of these simplifications are not known, but it is often assumed that streamlined LCA captures 70 to 80% of the opportunities for environmental improvement (Graedel and Allenby, 1995). However, one recent evaluation concluded that streamlined LCAs can have truncation errors as high as 50% (Lenzen, 2001). Further quantitative evaluation of claims that underlie these assumptions could define both when such assumptions provide reliable guidance and the type and extent of uncertainty that arises when they are used (Sousa *et al.*, 2001).

SUMMARY

A rigorous scientific foundation will be essential for the development of an environmental policy that may be increasingly linked to technology and economic policy. The U.S. EPA and the National Science Foundation have already begun to support research related to industrial ecology. (These include the joint NSF/EPA programs on Technology for a Sustainable Environment, Decision Making, and Valuation for Environmental Policy, Green Chemistry, Design For the Environment and Green Engineering, and Interagency Opportunities in Metabolic Engineering. In addition, the National Science Foundation's programs in Environmentally Benign Chemical Synthesis and Processing, Environmentally Conscious Manufacturing, and New Technologies for the Environment also address industrial ecology themes.) Significant

Table 1. Research needs in industrial ecology.

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| Testing the Assumptions of Industrial Ecology |
| Better understanding is needed of the potential for and limitations of |
| Dematerialization (reduction in the amount of material per product or activity), |
| Substitution of scarce or harmful resources with those that are plentiful and benign, |
| Recycling and reuse, |
| Substitution of services for products, |
| Technological innovation as an environmental management strategy, and |
| Voluntary approaches to environmental management. |
| Life-Cycle Assessment and Related Environmental Evaluation Approaches |
| There is a need for |
| Peer review of methods and software, |
| Standardized tests for methods and software, and |
| Development of a comprehensive life-cycle inventory database. |
| Better understanding is needed of the validity and limitations of |
| Metrics used to compare different environmental effects. |

advances in industrial ecology will require new theoretical developments, quantitative models, empirical research, and field-scale experiments. Neither a quantitative theoretical foundation nor a substantial body of experiment—in science or in policy—have yet been developed for this new field. The potential for scientific experiments has hardly yet been conceived, with most efforts currently at very small scales. The potential for policy experiments is somewhat more developed, with state-level policy innovations increasingly viewed as a venue for policy experimentation and adaptive learning.

We advocate research to test and refine the assumptions of industrial ecology and to strengthen basic applied tools. Research topics that could contribute to this goal are summarized in Table 1. With further development and refinement of the premises and methods of industrial ecology, this emerging field holds significant promise for improved environmental policymaking.

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