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Research Issues in Sustainable Consumption: Toward an Analytical Framework for Materials and the Environment

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We define key research questions as a stimulus to research in the area of industrial ecology. The first group of questions addresses analytical support for green engineering and environmental policy. They relate to (i) tools for green engineering, (ii) improvements in life cycle assessment, (iii) aggregation of environmental impacts, and (iv) effectiveness of a range of innovative policy approaches. The second group of questions addresses the dynamics of technology, economics, and environmental impacts. They relate to (v) the environmental impacts of material and energy consumption, (vi) the potential for material efficiency, (vii) the relation of technological and economic development to changes in consumption patterns, and (viii) the potential for technology to overcome environmental impacts and constraints. Altogether, the questions create an intellectual agenda for industrial ecology and integrate the technological and social aspects of sustainability.

Introduction

Sustainability has been widely endorsed as the over-arching goal of environmental policy. The hope—or vision—is that a strong, just, and wealthy society can be consistent with a clean environment, healthy ecosystems, and a beautiful planet. There has, however, been considerable doubt expressed about the potential for scientific research in this area. We argue that many key issues of sustainability can be expressed as tractable research questions that build on existing research. We develop a part of that research agenda here, drawing on the results of an NSF-sponsored workshop (*1*).

Although research in sustainability is inherently broad and multi-faceted, it falls naturally into three basic areas: use of materials and energy, land use, and human development. These three areas are inter-related, and in various contexts two or perhaps all three might be considered together (*2*). For the purpose of developing a clear and manageable research agenda, we focus here on one of the three areas—use of materials and energy. Research in this area, broadly termed industrial ecology (*3*−*5*), aims to understand how the environmental impacts of industrialized systems—including energy and transportation, consumer products, cities, and food production—can be understood, managed, and reduced over the long term. We will not enter here into the often contentious discussion of the exact meaning of or prospects for sustainability (*6*−*8*). Rather, we focus on reducing the environmental impacts of materials and energy use as a necessary component of sustainability and on the overall goal of developing an environmentally benign technological basis for contemporary and future societies (*9*, *10*).

We divide the discussion of industrial ecology into two broad categories of research: engineered systems and global systems. In the area of engineered systems, the underlying issues involve reducing the environmental impacts of products while simultaneously minimizing the costs of so doing. The relevant research relates to materials, products, or product categories, with the time scale of application typically a decade or less. In the category of global systems, the underlying issue is the long-term relationship between technological development, social and economic development, and the environment. We include in this category not only geographically global environmental problems such as climate change and stratospheric ozone depletion but also overall human health and welfare, the state of the economy, and resource availability.

In developing this research agenda, we have tried to select and define the issues as tractable research questions for which good progress can be expected over a 1−2-decade time frame. In our judgment, engineered systems research is relatively well-advanced in the areas of life cycle assessment and analysis of strategies for environmental management. The global systems research is at a less mature stage. As with other fields of science and engineering, the development of a theoretical and analytical framework for the use of materials and energy and the resulting implications for the environment will be a continuing process.

Within these two areas, we have defined a few key questions that we think will stimulate research in this field. These are listed in Table 1 and discussed below.

Engineered Systems

Research to reduce the environmental impacts of engineered systems spans a wide range of topics, disciplines, and levels of focus. As with all engineering design approaches, green engineering will always be a work in progress. New materials, new analytical capacity, and new product concepts will require appropriate responses from the engineering community. Here we discuss two aspects of research in this area that improve the overall basis for re-engineering of products, processes, and technological systems: (a) analysis of the environmental impacts of products and the potential for redesign of products and material management and (b) environmental management strategies.

Analytical Support for Green Engineering. To make processes, products, and material management more efficient and environmentally benign requires extensive redesign on a process-by-process and product-by-product basis (*11*−*13*). Much of this work is carried out by industry, although national laboratories and university-based research also play critical roles. In the case of refrigerators, for example, research at national laboratories, funded primarily by the U.S. Department of Energy, has made possible a two-thirds reduction in average energy consumption over the past 25 yr (*14*).

For refrigerators, the design goal was clear: refrigerators require a significant fraction of household electricity, and the environmental impacts of energy use are relatively well understood. But for other kinds of products and impacts,

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TABLE 1. Key Research Questions in Industrial Ecology

Engineered Systems
Which tools can designers use to develop environmentally preferable products?
How can life-cycle assessment be made more efficient, reliable, and comprehensive?
What are the absolute and relative merits of various approaches to aggregating environmental impacts?
Which policy approaches are most effective for reducing (which) environmental impacts?
Global Systems
What are the environmental implications of material use at national and global scales? Which resource flows are most environmentally damaging?
How can material use become significantly more efficient? Which wastes and stockpiles can be re-characterized as resources?
How are technologies and economic development driving environmentally significant consumption? In what materials, products, places, and time scales can we expect significant change in material and energy use or its impacts? Can key variables and functional relationships be identified?
To what extent can technological change overcome the environmental impacts of material and energy use? How can resource availability (or depletion) be characterized in a way that takes into account the potential for substitution and technological change?

the tradeoffs may not be so clear. To provide a framework for the re-engineering of particular products, there is a need to evaluate the environmental implications of different choices of materials, product design, and service format as well as choices regarding recycling, repair, and disposal. Considerable progress has been made in developing methods to design products and processes with the environment in mind and to assess the environmental implications of those designs. The key research issues at this point are development of applied tools for use by designers and decision-makers, validation of life cycle assessments, and validation of metrics for comparing different types of environmental impacts.

Which Tools Can Designers Use To Develop Environmentally Preferable Products? Just as a crucial step in the development of efficient, reliable product designs involved tools such as CAD/CAM, there is a need to develop applied design-for-environment tools for use by designers and decision-makers. Tools are needed for a wide range of materials, building and construction materials, commodity materials, polymers, functional hybrid materials, biobased materials, and electronic and photonic materials, and for a wide range of industry sectors including automotive, component fabrication, electronics, pharmaceuticals, and many others. The semiconductor industry, for example, cites a need for an “integrated way to evaluate the environment, health and safety impacts of processes, chemicals, and process equipment, and to make environment, safety and health a design parameter in development procedures for new equipment and processes” (*15*).

Some of the basic knowledge needed by designers and practitioners already exists, and some of it may already be available in tool form. However, discussions with environmental managers in industry indicate that such tools are not widely known nor widely trusted (*1*, *16*). There is a need to put together what is known in this field in a way that is accessible and useful to fundamental researchers, to tool developers, and to designers and practitioners. There is a need to integrate environmental choices into the decision process, including not only the design process but also corporate decisions, consumer decisions, and public policy decisions.

How Can Life Cycle Assessment Be Made More Efficient, Reliable, and Comprehensive? Environmental life cycle assessment (LCA) is the method by which the environmental impacts of different products or activities can be compared on a systematic basis. It is the analytical foundation of many environmental design tools. In principle, a LCA evaluates the entire environmental impact of a product through its life cycle, including manufacturing, use, and disposal. In practice, LCA has proven to be contentious, inefficient, and expensive. Moreover, it is not clear that all related factors, such as the waste disposal infrastructure, the temporal and spatial boundaries, and the context of the activity or product use, are adequately incorporated. 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. One of the main issues of LCA has been the validity and comprehensiveness of available life cycle inventory (LCI) databases, which are the basis for LCA studies but are neither standardized nor peer-reviewed. Efforts to address this need are currently underway; continued support of work in this area is needed (*17*, *18*).

What Are the Absolute and Relative Merits of Various Approaches to Aggregating Different Environmental Impacts? There is considerable scientific understanding of the environmental and health impacts of industrial pollutants, and of a range of industrial and human activities.However, it is often difficult to relate this knowledge to products and consumer activities. Most products have more than one type of environmental impact, and these impacts are usually incommensurate. There are ecosystem impacts, and there are human health impacts. There are varying levels of uncertainty associated with different environmental impacts. There are different types of human health impacts, including acute, carcinogenic, and developmental, that affect different groups of people differently. Some environmental impacts can be compared on a strictly scientific basis, but for many others a judgment must be made about their relative importance (*19*).

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 designed as 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 (*20*−*22*). Willingness-to-pay has been developed as an economic measure of environmental health impacts (*23*), and quality adjusted life years (QALYs) have been developed as a measure of health outcomes (*24*, *25*).

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. 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.

Environmental Management Strategies. *Which Policy Approaches Are Most Effective for Reducing* (*Which*) *Environmental Impacts?* Traditional command-and-control environmental policy aims to reduce pollution by setting a cap on emissions or by requiring pollution control devices. Some new environmental strategies aim for economically efficient environmental protection. Markets for pollutants have been successfully developed to reduce SO_2 emissions in the United States at low cost (*26*). Other new environmental strategies aim to promote innovation, not simply by controlling emissions but by encouraging the development of processes and product designs that are inherently clean.

It has been suggested that by selling a service rather than a product, firms could have an incentive to be more efficient with materials and energy. For example, an integrated pest management service might provide crop protection rather than selling pesticides per se. To evaluate the potential of service strategies to reduce environmental impacts, this approach needs further conceptual analysis and systematic empirical testing (*27*−*29*).

Another approach is to provide consumers with environmental information about products. Many programs to provide environmental information to consumers have been shown to be ineffective in changing behavior, so careful program design is now understood to be essential (*30*, *31*). A fuller understanding is needed of the potential and limitations of programs such as these and, more broadly, of the potential for social learning to reduce the environmental impacts of consumption.

A third approach may be to discourage some types of individual or corporate consumption through taxes. Examples might include taxes on fossil fuels or taxes on use of hazardous materials in products. Taxation as an incentive structure has been studied extensively within economics; there is a literature on tax shifting for environmental purposes (*32*). Experimental implementations of consumption taxes together with comparative analyses of consumption under different tax regimes could provide a quantitative understanding of the potential of tax incentives as an environmental strategy.

Additional approaches include the reuse of products, the recycling of products, efficiency improvements in industry, and a range of voluntary industry/government environmental programs. The OECD Environment Directorate reports that policy initiatives to promote more sustainable consumption patterns have been only mildly effective (*33*−*35*). There is a need for rigorous evaluation of these strategies, to understand both their potential and their limitations (*36*).

Global Systems

The long-term relationship of the environment to technological, social, and economic development is a core environmental issue. Quantitative analysis may not be feasible for some aspects of this relationship, such as the environmental implications of genetic engineering, nanotechnology, or other new developments. But other aspects, including the environmental impacts of material and energy use, and the drivers of consumption can be expressed as tractable research problems. Below we discuss material cycles as a basic analytical framework and the evolution of consumption of material and energy as an over-arching research theme.

Budgets and Cycles for the Materials of Technology. Material budgets and cycles are a basic approach to evaluating large-scale environmental impacts and resource issues (*37*). Research on materials cycles overlaps with research on the major biogeochemical cycles, such as carbon and nitrogen, although materials cycle research includes a wider range of materials and puts greater emphasis on human activities. A material budget assesses material flow in to and out of a single reservoir; a material cycle assesses flows among several reservoirs. Important reservoirs include atmosphere, soil, mines, oceans, built infrastructure, landfills, human tissues, and food chains for humans and other species. Research involves not merely quantifying use and disposal of materials but also understanding the mechanisms that control the transport among reservoirs, the mechanisms that relate materials use to impacts, and the mechanisms through which materials use might change.

In recent years, natural scientists have constructed cycles for the "grand nutrients": carbon, nitrogen, sulfur, and phosphorus. The results have provided scientific understanding and a basis for policy initiatives. In a similar way, it is valuable to construct cycles for the materials of modern technology: metals, plastics, renewables, etc. (*38*, *39*). The results would provide insight on resource use rates and losses to the environment and guidance for policy decisions related to the materials cycles.

What Is the Environmental Implication of Material Use at National and Global Scales? Which Mass Flows Are Most Environmentally Damaging? A key motivation for studying material budgets and cycles is to understand environmental impacts. But budgets and cycles do not in themselves provide information on environmental impacts. They simply quantify the flow of materials going in to and out of reservoirs and do not provide insight into the differences between the cycles, impacts, and implications of renewable and nonrenewable resources.

Making the link between material cycles and environmental impacts can require knowledge from several disciplines. A particular challenge is to account for chemical transformations in which the environmental impacts of elements or compounds change dramatically as they are transformed from one chemical state to another (e.g., chlorine in salt and in dioxin). But if the motivation for material cycle research is environmental, then it is essential to develop a robust quantitative relationship between the material cycle and the environmental impacts. In some cases, material use is interpreted as an environmental "indicator", with all material flows or environmental emissions implied to have comparable impact. Rigorous analysis of these impacts will mark the maturation of material flow research.

One approach to linking material cycles to impacts is to start with a global measure of environmental impacts and work back to find linkages to material cycles. In the area of human health, disability-adjusted life years (DALYs or QALYs) might be used to relate a wide range of environmental emissions to human health impacts on a consistent basis (*24*, *25*, *40*).

Understanding the scaling of environmental assessments, from the level of activities and products to the level of economies and regions, will require significant methodological advances. The environmental impacts of some products are fairly well understood, but product-level assessments cannot currently be scaled beyond a limited set of related products. Scaling a product-level analysis to the level of the entire economy would not be completely simple and linear since economy-scale interactions would need to be taken into account (*41*). The product-level analyses do not yet connect to national-scale material flow analyses and do not take into account the influence of macro-economic changes on material flow and environmental impacts. Understanding which variables are appropriate for scaling analysis and how they can be consistently defined, applied, and evaluated at multiple scales would provide a basis for integrating engineering, economic, and environmental variables (*42*, *43*).

Much of the research in industrial ecology has been focused on the highly industrialized countries. However, the impacts of energy, technology, products, and wastes are increasingly global, and as industrial production has become global, the associated environmental impacts have become global as well. To address the impacts of materials, energy, technology, and products, the analytical scale must correspond to the physical scale of the impact.

How Can Material Use Become Significantly More Efficient? Which Wastes and Stockpiles Can Be Recharacterized as Resources? Another aim of material cycle and budget research is to identify recycling opportunities and to understand how they might relate to resource and energy use minimization on a global basis. There have been a number of suggestions that materials could be mined from cities or landfills (*44*–*46*). Allen and Behmanesh (*47*) have pointed out that the concentrations of metal resources in many waste streams are higher than for typical virgin resources. Better understanding of the status, composition, and location of wastes, stockpiles, discards, and of the institutional and organizational requirements for access could open a wealth of opportunities for recycling and reclamation.

One approach to understanding the potential for greater efficiency is to analyze industrial "food webs". Biological ecologists use food web analysis to understand the linkages among species and the interspecies resource transfers that occur. In roughly analogous ways, industrial species share metals, plastics, paper, and other resources in systems where linkages might be revealed by extensive industrial food web analysis.

An approach to increasing the efficiency of manufacturing is the eco-industrial park (*48*). It has been suggested that the reuse of industrial residue streams can be enhanced by carefully planned eco-industrial parks, but there are as yet few data to support this conjecture. The input, output, potential flows, and spatial and temporal evolution of existing eco-industrial parks of all types need to be collected, grouped, analyzed in detail, and integrated into the municipal planning and development process.

Evolution of Consumption. *How Are Technologies and Economic Development Driving Environmentally Significant Consumption? In What Materials, Products, Places, and Time Scales Can We Expect Significant Change in Material and Energy Use or Its Impacts? Can Key Variables and Functional Relationships Be Identified?* Material and energy use will change over time. Since the 1970s a growing body of research has suggested that greater material efficiency, use of improved materials, and growth of the service economy are contributing to the "dematerialization" of the economy. A related body of research suggests that expensive, scarce, or environmentally harmful resources may be able to be replaced by resources that are cheap, abundant, and environmentally benign. "Substitution" can be seen in the changes in energy sources that have occurred over the past century. As those sources have shifted from wood and coal to petroleum and natural gas, the average amount of carbon per unit energy produced has fallen, resulting in a "decarbonization" of world energy use (*49*).

There have been many attempts to alter consumption patterns to reduce environmental impacts. But here is no overall understanding of how far these efforts might go and whether there are fundamental limits or obstacles to the potential to change consumption patterns to reduce environmental impacts (*50*, *51*). Some of the issues related to changes in consumption patterns are discussed in section 1 on environmental management strategies. Beyond the short-term changes that might be induced by innovative policy approaches, there is a need for understanding of the longer-term drivers of change in consumption patterns. It has been argued that people worldwide are making a transition from "materialist" to "post-materialist" values, with increasing emphasis on nonphysiological needs such as esteem, self-expression, and aesthetic satisfaction rather than material needs for physiological sustenance and security (*52*, *53*). But even if values and beliefs do change, how much will material and energy consumption change?

One approach to understanding the potential for changes in materials use is to analyze the metabolisms of cities (*54*). Cities are known to be strong attractors of resources and weak dispersers of them. If we think of cities as organisms, however, we have little quantitative information on their metabolisms. Establishing the metabolic differences between cities in different parts of the world, of different sizes, and in different stages of evolution could help us better understand the current diversity in material use patterns.

Changes in material and energy use will have general equilibrium effects as income reallocated from one form of consumption is either saved or spent on something else. There is need for a better understanding of "rebound" effects, in which an environmentally beneficial design proves so desirable for that or other reasons that increases in production swamp the product-level environmental gains. (Rapidly increasing numbers of vehicles with improved emission control systems is an obvious example.) Ultimately, the challenge is to understand the extent to which consumption can be decoupled from environmental impacts while raising the quality of life. Integration of economic and physical analyses could provide a comprehensive framework for understanding the relationship of environmental, economic, and technological change. Hamilton and Clemens (*55*), for example, have developed an approach that integrates resource depletion and environmental degradation into national accounts of savings and wealth.

To What Extent Can Technological Change Overcome the Environmental Impacts of Material and Energy Use? How Can Resource Availability (*or Depletion*) *Be Characterized in a Way That Takes into Account the Potential for Substitution and Technological Change?* There is increasing understanding that resource constraints are complex and interdependent: that one resource can be substituted for another and that resource availability depends on the technology of resource extraction (*56*). There is a need for more rigorous understanding of the overall potential and limitations of resource substitution, the potential and limitations for market forces and technology to overcome physical depletion of particular resources.

More broadly, claims and counterclaims about the need to constrain the consumption of materials and energy have characterized the most heated environmental policy debates. At one pole, it has been suggested that consumption of materials and energy in developed countries needs to be significantly reduced in order to protect and maintain environmental systems. At the other pole, it has been suggested that technological innovation will allow us to reduce environmental impacts without reducing economic growth or use of materials and energy. Neither of these extreme views is likely to be very useful. In some cases, technological innovation can surely obviate the need for constraints on consumption. In other cases, constraints on consumption (through, for example, energy taxes or restrictions on use of certain kinds of chemicals) can in themselves drive innovation. The development of a theoretical foundation for understanding the relative roles of technological innovation and consumption constraints in meeting environmental goals would provide a stronger basis for the long-term development of effective environmental policy (*57*).

Discussion: Toward an Analytic Framework for Sustainability

In the discussion above, we have focused on material and energy use, and we have not addressed the other two major topics of environmental sustainability: human development and land use. Ultimately, in the development of an understanding of the relationships of technological innovation, economic development, and environmental protection, it will be necessary to include all factors in the analysis. To date, most analyses of the environmental impacts of material and energy consumption have focused on the habits of the rich world. However, it is in the developing world that growing demand for energy, materials, and technology will test the proposition that economic development can be environmentally benign.

Moreover, while it is obvious to evaluate material and energy use in terms of the direct impact of environmental releases, in a broader sense it is the development of new technologies and the use of materials and energy that leads to habitat destruction and ecosystem stresses. There is a strong and direct link between industrial ecology, land use, and ecosystem protection, not only in the areas of agriculture and forestry but also in the areas of transportation systems and in urban and suburban planning (*58−61*). To ignore land use and ecosystem impacts in the analysis of material and energy consumption could greatly limit the relevance and impact of the research.

In short, the major environmental questions regarding material and energy use, human development, and land use are inherently linked. Some of these questions can be appropriately addressed in isolation, and limited early studies can provide a platform for more comprehensive analyses. With the questions identified here, we hope to stimulate and encourage rigorous research on sustainability and material and energy usethat can provide a foundation for future policy development.

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