

Industrial Ecology and Global Change

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OVERVIEW

Six Perspectives from Industrial Ecology

Robert Socolow

Exploring Industrial Ecology

People are great rearrangers of the earth. Metals that have been locked away in the veins of rocks over the eons of prehistory are mined, freed from their oxide or sulfide drabness, and allowed to shine or cut or channel electrons for our pleasure, for a few decades at most, before being dispersed without plan in soils and streams. Porous sediments more than a kilometer below ground, soaked with oil or laden with natural gas, are penetrated by drill holes to release their burnable contents; people are provided mobility or comfort for a brief moment by the energy accompanying the oxidation of these fuels, and in less than a century the global atmosphere registers five molecules of carbon dioxide for every four that were there before. Chemicals that never existed in the history of our planet are synthesized for the killing of weeds or insects, or for the cooling of transformers. Radioactive isotopes that had decayed to oblivion early in our planet's history are recreated, as the fission of uranium provides another source of electricity and heat. *Industrial ecology* is a metaphor for looking at our civilization through such lenses.

The metaphor of industrial ecology also leads us to look at interrelationships. The interrelationships among producers and consumers determine what becomes waste and what is usable, and how the "natural" is combined with the "synthetic." Industrial ecology explores reconfigurations of industrial activity in response to knowledge of environmental consequences. It is intended to stimulate the imagination and enlarge the sense of the possible, with regard to industrial innovation and social organization. It offers a fresh view of environmental management.

Industrial ecology provides six perspectives:

Long-Term Habitability

The dominant perspective for environmental analysis expands in time: from short-term insult to long-term habitability. Priority issues include persistence of toxic chemicals, depletion, and disruption of grand life-supporting cycles.

Global Scope

The dominant perspective expands in space, from local insult to regional and global impact. "Global" is used in both the sense of global spatial scale (climate) and

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problems found universally on the globe (pesticides, urban air quality). Economic development paths for the less developed countries receive special attention.

The Overwhelming of Natural Systems

Nature is the measure of man. To overwhelm implies a focus on a ratio, changing over time, that compares some human enterprise with, typically, some pre-existing characteristic of the natural environment. Such ratios complement the traditional indices of economic activity.

Vulnerability

Man is the measure of nature. Vulnerability, and its opposite, *resilience*, establish an appropriately comprehensive scale to evaluate the significance of natural hazard, ecosystem disruption, and disease, for countries, communities, institutions, and individuals. Vulnerability addresses the overwhelming of *human* systems.

Mass-Flow Analysis

Materials are tracked relentlessly through time and space. Mass-flow analysis, well known in chemical engineering, builds on the conservation laws of classical physics (mass cannot be destroyed, atoms are stable, energy can be degraded but does not disappear).

Centrality of the Firm and the Farm

The industrial firm and the industrial farm are put on an equal footing with the household/consumer/voter. The view of the firm and farm changes from culprit to agent of change.

These six perspectives will be outlined in this brief essay, with an emphasis on the concepts they highlight and the integrative frameworks they reveal. The chapters that follow will demonstrate these perspectives in action, in industry and in government. In the aggregate, these six perspectives add up to "new thinking." The contrast, here, is with the more narrowly conceived environmental management perspective ("old thinking") that has been dominant for the past two decades.

The new thinking is as radical for the environmental activist as for the industrialist. The legacy of two decades of environmental regulation is a system of environmental management that has accommodated the strategies of many interest groups. The focus of attention has long been on production facilities—conveniently far from the point of consumer involvement. By contrast, industrial ecology emphasizes the management of products throughout their useful life and beyond, and calls attention to dispersed sources of pollution, such as agricultural chemicals, household wastes, and the chaff resulting from the expected degradation of products like outdoor paints, roofing materials, and brake linings. The importance of the consumer is unmistakable. Rage at the industrial producer recedes in significance as a driver of policy.

Any claim to "new thinking" deserves to be treated with skepticism. Is there

something new here, or just a repackaging of common sense? How well grounded are these six perspectives? Is an elitist preference system being proposed, masquerading as rationality? How promising is *any* program advocating rationality, in an irrational world? Won't the program envisioned here be undone by a rage directed against environmentalist-industrialist alliances that interfere with ordinary living? Such doubts cannot easily be dispelled. The ultimate value of the these six perspectives will be established by their ability to transform the environmental agenda in productive directions.

Long-Term Habitability

Environmentalism has been fueled by short-term insult: the beach made unusable by sewage, urban air that keeps children from playing in schoolyards, gasoline lines that result when world energy markets go awry. Industrial ecology addresses a different dimension of environmentalism, not short-term distress but long-term habitability. Quantitatively, attention to habitability stretches the time frame of concern to several decades, even a century. While such a time frame is rarely encountered within local and national environmental regulatory regimes, it is the time frame underlying recently proposed international environmental agreements, such as in climate and forestry. In adopting the framework of habitability, industrial ecology is borrowing a central concept of global change research and inserting it into pragmatic realms like industrial development and environmental regulation.

Persistence and Chemical Toxicification

Although much less familiar as a global issue than climate modification, toxification of the environment is another chemical path to loss of habitability. Toxification stalks global change research and is gradually achieving greater prominence. Toxification of soils is one concern: Little is known about the extent to which future nutrient imbalances and loadings of metals and chemicals will diminish the yields currently obtained on agricultural land. Toxification high up the food chain is another concern: Many persistent chemicals concentrate in the food chain, and some of these chemicals reach toxic levels in such varied organisms as raptors, large fish, and human beings. Direct toxification of human environments without the intermediary of environmental processes is a third concern: When persistent chemicals find industrial uses in stable settings, as with lead in the paint on old buildings, the innocent practices of one generation become the hazards of the next.

None of these forms of toxification would occur without durable industrial materials. Yet achieving durability used to be an unquestioned objective of industry. We have been re-educated by the story of the chlorofluorocarbons (CFCs, such as Freon), introduced into the modern economy as refrigerants, foaming agents, spray-can propellants, and cleaning agents, largely because they were not combustible or toxic or reactive with other chemicals. The most widely used CFCs are

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now being phased out because of their capacity to thin the ozone layer in the stratosphere. It turns out that the same inertness that makes CFCs desirable industrial products allows them to rise intact into the stratosphere, instead of succumbing to the chemical assaults in the radical-rich oxidizing environment of the lower atmosphere that transform most other molecules. We now understand that durability can be a two-edged sword.

Depletion and Physical Degradation

The inhomogeneities of the physical world are the natural endowment of the human species. For many elements, the accessible sites of unusual excesses over average crustal concentrations have become commercial mines. Unusually capacious aquifers have become water supplies. Extraordinary accumulations of fossil fuels have become active drilling provinces. With industrial activity, our natural endowment is dissipated. In the language of thermodynamics, industrial activity is increasing the earth's entropy, making it more similar from place to place. A small exception is where human activity creates a new kind of mine for some future society by reconcentrating an element in a dump or landfill.

Human activity produces not only chemical, but also physical degradation of habitability. Topsoil is blown away. Riverbanks are eroded. Land subsides at sites where natural gas is extracted or water is removed from aquifers. Water is lost from river valleys by evaporation at lakes behind dams. Lakes and inland seas shrink in size (the Aral Sea is a notorious example) when their water sources are diverted for irrigation.

Extinction and Biological Simplification

Loss of habitability is above all a biological issue. Here, more than with chemical or physical degradation, one confronts irreversibility, in the form of loss of species. Loss of species diminishes the robustness of ecosystems. It also removes from the human future a source of enjoyment, education, and possible direct material benefit. In principle (but rarely in practice), one could use some energy source in very large amounts to reconcentrate a mineral resource or to reconstitute an aquifer. Not even in principle can one recover lost species.

Unlike most chemical and physical degradation of the environment, ecological degradation can be abrupt. Fish populations can plunge suddenly when potent industrial maritime technologies for "harvesting" the oceans are introduced. Like physical degradation, biological degradation is, in part, a matter of lost variability and increased entropy. When an ecological system rich with endemic species loses its isolation by breaches at its boundary or by the introduction from afar of common, hardy species, it soon loses its distinctiveness.

When can loss of habitability be reversed? This question is central to the rehabilitation of formerly productive and biologically diverse ecosystems that are now degraded and simplified. In the United States managers of rangelands, forests, and

fisheries have been gradually changing their objectives, away from new production and toward rehabilitation and repair. The new objectives are unfamiliar. Highway builders long resisted shifting their attention from the building of new roads to repair and maintenance. But shift they did. So, now, with land and sea.

Global Scope

Most of the impetus to restructure industrial processes continues to come from local impacts: to make a factory into a better neighbor, to comply with local regulations on emissions, to facilitate the siting of facilities in the face of the "Not in My Back Yard" syndrome (NIMBY). Industrial ecology adds an unfamiliar, yet refreshing, challenge by asking which of the strategies of environmental control that emerge in response to local and regional concerns are further justified by global concerns. The dominant perspective expands not only in time but also in space.

Global change research has traditionally addressed two kinds of global systems: (1) systems intrinsically as large in size as the earth, and (2) small but ubiquitous systems. However, research into small, ubiquitous systems, such as rice fields, has focused nearly exclusively on their capacity to induce changes in systems of the first kind, especially climate. Global changes brought about by changes in small but ubiquitous systems not mediated by climate have generally been neglected, such as changes in agricultural practices that could be affecting soil productivity everywhere. A broader framework for global change research would include all disruptions that are ubiquitous, that result from human activities that are themselves ubiquitous, and that have cumulative effects of worldwide significance. Admitted into the canon, for example, would be investigations of the extent to which the various metals mobilized by industrial activity have worldwide deleterious impacts on ecosystems.

Increasingly, local-scale disruptions share common characteristics at sites spatially far apart, because industrialization varies so little in its details from country to country. New automobiles and fuels, new agricultural practices, and new tax structures spread quickly around the world. Everyone is imitating everyone else. Accordingly, studies of the planetary impacts of ubiquitous disruptions of local-scale systems become increasingly important.

Inextricably embedded in a global perspective is an egalitarian morality: everyone, everywhere counts. Industrial ecology integrates over all individuals and all nations. The world's resources are everyone's entitlement and everyone's responsibility. Everyone has a stake in the world's future population and its distribution, as well as in how each of us chooses to live.

With few exceptions, all individuals today wish to live like individuals materially richer than themselves. And all nations aspire to resemble the wealthiest nations. These central facts add portent to the choices among paths of industrialization and population growth made in the less developed countries, and among paths of industrial intensification made in the already industrialized countries. Departures from business as usual are necessary in all countries, at every level of industrialization.

The global perspective of industrial ecology calls attention to the need to combine research on physical systems of global significance with related social science. Behavioral science can be asked to explore how individuals integrate their self-centeredness and tribalism with global concerns. Policy science can be asked for critical assessments of international public and private institutions, with particular attention to their effectiveness in fostering innovation. There is an urgent need to identify, for all countries, effective strategies to build human capital and institutional capacity and to acquire and disseminate information and technique. Lessons can be sought from the international institutions currently at the service of agriculture and public health. As explained in the chapter by Golitsyn (this volume), military conversion offers opportunities, such as augmented capabilities in instrumentation and analysis; these merit attention.

The Overwhelming of Natural Systems

Industrial ecology puts "people" and the "nonhuman environment" into the same picture. Thereby, it gives rise to a set of useful hybrid concepts that capture the interactions of one with the other. Two hybrid concepts are particularly useful: the concept of the overwhelming of natural systems by human activity and the concept of the vulnerability of human systems to natural processes.

In the present period, human beings are perturbing the planet's natural processes significantly on a global scale. We are overwhelming both regional and global environmental systems: lakes, airsheds, fisheries, forests, the ozone layer in the stratosphere, global climate. Our planet has become uncomfortably small.

A central line of inquiry within industrial ecology is directed toward understanding in detail which natural systems are particularly sensitive and therefore likely to be overwhelmed, and how they are affected by particular human activities that appear likely to grow substantially as a result of industrial development. For the first undertaking—identifying sensitive components of the natural environment—environmental science has made some educated guesses: three examples are stratospheric ozone, the Arctic ice cap, and the soil of tropical forests. Today's list is surely incomplete, and it will be improved by a deeper understanding of nonlinear systems. For the second undertaking—identifying fast-growing impacts of human activity—history is one guide, demography a second, and cross-cultural studies of economic development are a third.

Remarkable long-term data sets, such as those related to energy intensity and fuel use, have been teased out of historical records. As the chapter by Grubler in this volume attests, these data sets give helpful insights regarding the engines of industrial growth and the patterns of spread of industrial practices.

Complementing historical studies are the efforts of demographers to relate population, migration, and urbanization to agricultural and industrial activity. Of greatest importance is the total number of people. The need to feed growing numbers of people, for example, drives the intensification of the use of fertilizers and other agricultural chemicals. Indeed, the prevailing methodology for describing

environmental consequences of human activity first analyzes per capita activity (diet, habitat, mobility) and then multiplies by total numbers of people. With the greater involvement of demographers, a more refined analysis could be developed that takes into account age structure, family size, population density (both sprawl and crowding), migration within countries and across borders, and other demographic variables.

Cultural studies are a further important component of the analysis of levels of human activity and their consequences. A small set of resource-intensive strategies dominates economic development today, with no rivals, in agriculture, construction, transportation, communications, and other economic sectors. If alternative, less resource-intensive strategies were to be adopted widely, the consequences could include significant reductions in the rates at which, globally and locally, human activity overwhelms natural systems. Cultural studies can identify circumstances where such alternative strategies might be invented by societies blending modernization with preindustrial traditions.

The task of comparing present and potential levels of human activity to thresholds, absorptive capacities, and other quantitative measures of stress on the natural environment is one of the frontiers of industrial ecology. To make progress requires modifying the modus operandi that separates research in natural science from studies of economic development. Natural scientists would surely be giving greater priority to studies of the nitrogen cycle today, for example, if they better appreciated the relentless growth in the production of nitrogen fertilizer that accompanies the intensification of agriculture.

The task of clarifying, case-by-case, the meanings of "overwhelm" abuts another task, that similarly requires a new kind of collaboration, and to which we turn next: What determines how much strain the stresses on a natural system will cause individual human beings, their communities, and their institutions?

Vulnerability

The historical records of natural disasters and, to a limited extent, mathematical models of the weather system, document the frequency of occurrence of acute events such as floods, hurricanes, and typhoons, as well as more chronic departures from average environmental conditions such as prolonged droughts, the accumulation of salts and metals in soil, and a rise in sea level. Elaborate technical apparatus is available to the natural scientist to summarize the implications of this information in probabilistic statements of risk: the height of a river in a "hundred-year" flood, for example.

Such risk analysis for communities is seriously incomplete as a description of the human suffering and economic cost that accompanies nature's excesses. It leaves out any analysis of the capacity of one community to recover from a catastrophe that would devastate another community. One has only to compare the human impact resulting from the Mississippi floods in the summer of 1993 with those from the episodic monsoon floods over the Ganges delta in Bangladesh.

Vulnerability analysis complements risk analysis: It seeks to understand the capacity of a country or community to protect against and cope with both acute disasters and continual incremental environmental changes.

Vulnerability culminates a chain of concepts of increasing inclusivity describing the indirect consequences for human society of the direct environmental manifestations of day-to-day human activities. First, there are measures of *emissions*, rates of introduction of pollutants into the environment; emissions are the target of most environmental regulatory activity and industrial response, as in automobiles and electric power plants. Next, with the addition of an understanding of dispersal and concentration mechanisms in air, water, soil, and industrial practices, emissions are linked to *bioavailability*, a measure of potential for impact on ecosystems and human beings. Linked to bioavailability are *exposure* and *dose*, measures of actual impact that reflect where plants actually grow and what chemicals they mobilize, what people and animals eat and drink, and where they breathe or swim.

Attached to the link from bioavailability to dose is the link from dose to *incidence of disease* and *incidence of loss of ecosystem function*. To develop an understanding of this link requires toxicology and ecotoxicology. Ecotoxicology today is extending knowledge of chemical effects beyond our own species (and a few others studied in medical research) to other species, and beyond individual species to ecosystems. Toxicology is extending our knowledge of human impacts beyond cancer to other biomedical systems.

Thomas and Spiro take us along this part of the chain, in their chapter in this volume, through an analysis of lead that begins with emissions and gets as far as impacts on human health and ecosystem function. Small and particular uses of lead are responsible for most of the environmental damage due to lead moving through the economy. Two examples are the use of lead in gasoline, which becomes particulate lead in urban dust, in turn eaten by young children; and the use of lead in hunters' shot, that becomes lead embedded in the flesh of birds, in turn eaten by other birds. Damage from such uses dominates the damage from other uses of lead in the industrial economy, such as in batteries, that are larger in magnitude but less well linked to ingestion and inhalation.

An analysis of air pollution that considers total exposure and its health impacts, rather than terminating with emissions analysis, leads to a similar shift in attention, in this case from emissions of pollutants into outdoor air to inhalation of pollutants in indoor air. Emissions from cooking, radon drawn into buildings from the soil below, "passive" cigarette smoke, and formaldehyde from furniture and carpets are identified as significant sources for human beings, when a 24-hour-average daily dose is constructed.

When we are determined to confront consequences of damage, rather than only levels of damage, we are brought to the final link in the chain, a link that connects incidence of human disease and ecosystem disruption to *vulnerability*. To make progress exploring vulnerability, and its opposite, *resilience*, requires the further incorporation of social science. Will an ecosystem malfunction be recognized, and

are there resources available for restoration? In the case of human illness, are resources available for medical care? Will the illness lead to stigmatization or be socially accepted? The insights from environmental and medical sciences that link emissions to incidence of disruption and illness are made complete by an understanding of how communities and individuals handle stress.

To understand vulnerability requires cultural understanding, including an understanding of wealth and poverty. It also requires an understanding of dysfunctions within communities at all levels of industrialization—dysfunctions such as the domination of waste management by organized crime, and the domination of decisions about the use of chemicals by the purveyors of chemicals.

The better we understand vulnerability, the more effectively we will be able to intervene at an early link in the chain. There is a role, for example, for warning systems and for buffering capacity. What kind of warning system can alert society to vulnerability that is created incrementally, by cumulative effects that extend over several human generations? How can a robust buffering capacity be designed into the management of a natural system, like a river and/or airshed, so that society has room to maneuver and to accommodate environmental surprises and unforeseen future demands?

Mass-Flow Analysis

Industrial ecology seeks a unifying analysis, based on *total flows of materials*, that treats on a common footing all sources, all transport media, and all receptors. For this purpose, mass-flow analysis is proving to be a productive integrative tool.

Mass-flow analysis necessarily focuses on forms of matter that are either indestructible (chemical elements) or persistent on a scale of months to decades or longer (nonchlorinated organics such as methane, and chlorinated organics such as the chlorofluorocarbons and the polychlorinated biphenyls). An application of mass-flow analysis to cadmium in the Rhine Basin is found in the chapter by Stigliani, Jaffé, and Anderberg in this volume.

The analysis of mass flows builds on a previous success in the analysis of energy flows. But mass-flow analysis is more complicated. Generally, there is no interest in an energy flow beyond the point of use, where energy is usually degraded into heat. But mass-flow analysis continues beyond the point of use, because of chemistry-dependent behavior in the environment that affects toxicity. Mercury can be remobilized, as methyl mercury, after apparent discard on a lake bottom; chromium in the environment can become more toxic as a result of a change in valence.

Inevitably, scholars will extend and refine mass-flow analysis in the next few years, at least to the level of comprehensiveness already attained for energy flows: from the mine to the discarded product; at all geographic scales (from facilities to towns to islands and river basins to countries) and in all regions of the world; preindustrial baselines; scenarios of future flows. Ultimately, mass-flow analysis may develop enough downstream capability to be able to track materials through

air, water, and soil and to take into account chemical changes that affect solubility, bioavailability, and toxicity. Even then, it will be crucial to combine mass-flow analysis with exposure analysis to avoid missing small flows that happen to be environmentally significant.

The framework of mass-flow analysis has powerful, even subversive, implications for pollution policy. It treats with indifference both what is easy to regulate and what is hard to regulate. In cases where mass-flow analysis reveals the dominance of nonpoint sources over point sources, the focus of pollution regulation may shift to the farm, with its dispersed use of chemicals, and away from the factory, where pollution enters the environment through pipes and stacks. Even more unsettling are the implications of mass-flow analysis in cases where the wear or disposal of goods dominates other releases into the natural environment. This may shift regulatory attention from *production* to *product*.

In part, these shifts of emphasis are a consequence of the success of the first round of environmental control. Point sources are being significantly reduced by initiatives in industry and by regulation, making nonpoint and dissipative sources relatively more important.

Braungart's chapter in this volume takes some first steps in imagining a policy regime sensitive to the insights of mass-flow analysis. He proposes that consumer durable goods—like automobiles and television sets—be leased, not owned, so as to increase the likelihood of recycle and reuse of the many embodied chemicals.

Centrality of the Industrial Firm and the Industrial Farm

Economics and sociology have shed much light on industrial firms and farms as economic actors and as human institutions. Yet very little of this insight has informed the analysis of environmental problems and the design of environmental policy. *Environment* has been framed as a struggle between good and evil, where fault lies entirely with "industry" and not at all with John and Jane Public.

Industry, for the most part, has colluded in this drama, casting itself as helpless victim of misguided public outrage. Industry has rarely stepped forward to organize the debate—failing, for example, to add its abundant expertise to the first stages of discussion of environmental goals. Its posture vis-à-vis environmental policy has generally been: Tell us what you want us to do, assure us that our competitors will be required to do the same thing, and we will do the job.

The result has been an underutilization of technological capability in environmental strategy, with unfortunate consequences. To give a single example, a requirement of "best available control technology," which the layman would reasonably expect to induce continuous competitive innovation to control pollution at ever lower costs, turns into a recipe for freezing technological innovation, because the certification of "best" is so encumbered that whatever was declared "best" years ago is "best" for a very long time.

In industrial ecology, industry becomes a policy-maker, not a policy-taker. Industry demonstrates that environmental objectives are no longer alien, to be

resisted and then accommodated reluctantly. Rather, these objectives are part of the fabric of production, like worker safety and consumer satisfaction.

Detailed reports from the industrial frontlines, including several in this volume, offer important insights and challenge simple theories of the firm. At Volvo, industry is inventing design tools to prioritize among environmentally responsive investments, without waiting for precise and transparent methodology. At Dow, industry is achieving savings with short payback periods from environmental investments, with no sign of diminishing returns. At Hewlett-Packard, industry is designing for recyclability and ease of disposal. Reports such as these are invaluable for the crafting of policies that elicit environmental initiatives from industry.

Industrial ecology identifies roles for new industries, including (1) service industries offering efficiency and cost-savings in resource management, and (2) industries fostering renewable energy.

Service Industries Offering Efficiency and Cost-Savings in Resource Management

A service industry has already emerged to provide efficient energy use. Until very recently, around the world, electric utilities were concerned only with electricity supply and saw no role for themselves on the customer's side of the electric meter. Today, the relationship between electric utilities and the owners of commercial and residential buildings is often mediated by an "energy service company" which brings expertise in energy-conserving investments, like low-energy lighting and motor controls. Typically, the service company is either owned by or compensated by the utility, on the grounds that these investments help the utility to avoid the costs of new capital facilities.

Underlying the economic viability of the energy service company are policies embedding the novel concept of "least-cost" provision of amenities, like lighting or well-preserved food. Investments in energy-efficient light bulbs and refrigerators are traded against investments in power plants. Frequently, the investments made at the behest of energy service companies turn out to be justified even without taking into account their energy savings: a more controllable motor permits cost savings through more finely tuned operations. Yet it takes an external stimulus to get expertise directed toward a secondary area of business.

Analogous service industries are beginning to emerge to manage persistent chemicals. An intermediary between a chemical company and a farmer will offer the amenity of a certain crop yield. It will then, internally, trade the provision of fertilizers and pesticides against chemical-conserving, knowledge-intensive investments like genetic selection, biological pest control, and techniques to reduce crop spoilage. In a pollution control regime based on tradable permits for the discharge of chemicals, with caps on total rates of use, a service company might prosper as a dealer in pollution rights. Even in the absence of such a regime, the service company's expertise may produce profits, which the farmer and company can share, from reduced purchases of chemicals.

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There should also be a place in the near future for another class of service companies, managing the discard of goods. Consider, for example, our earlier example of the leasing of television sets: a new kind of service company might be an intermediary between the manufacturer of television sets and the watcher of television, adding the service of final disposal to the service of maintenance. Such a service company would have an economic interest in the producer minimizing the incorporation of low-value, high-volume wastes. In one possible configuration, the intermediary, at the time of retrieval from households of sets that have broken or become obsolete, might obtain pollution credits for avoiding discard of hazardous chemicals. Such specialized industries at the interface between the consumer and the manufacturer are analogous to the decomposers in an ecosystem.

Renewable Energy

Research and development are bringing into view a rich menu of clever ways to collect and transform the energy in sunlight cheaply, efficiently, and in environmentally responsible ways (see Johansson *et al.*, 1993). If renewable energy is to dominate the global energy scene, it will have to be embedded in the world's industrial energy system, centrally managed and grid-connected. In the terms of Amory Lovins's dichotomy of "hard" and "soft" paths (the hard path characterized by large spatial scale, centralization, and management by elites), we will have "hard solar" (Lovins, 1976).

Technologically, "hard solar" could appear in several forms. It could take the form of large arrays of solar thermal collectors, focusing sunlight onto "power towers," where the high temperatures permit efficient thermal cycles based on gas or steam turbines. Or, it could take the form of arrays of large windmills on tall towers. Or, biomass plantations and associated facilities (much like oil refineries) that convert biomass to high-value gases and liquids, as described in the chapter by Williams (this volume). Or, large arrays of photovoltaic collectors—plantations of glass—converting sunlight, via semiconductors such as amorphous silicon, directly to electricity. Commercialization is expanding rapidly on all of these fronts.

One of the most open frontiers of industrial ecology lies where renewable energy production can be combined with land rehabilitation. A project designed to meet both objectives should provide both energy and land repair at lower costs than projects designed for either objective alone. The economic viability of renewable energy projects located on degraded land will depend, in large part, on the extent to which land repair can be documented and monetized. The implications for the employment of specialists are clear: whether a project's renewable energy objective is to harness the wind or to collect sunlight directly or to process biofuels, its success will depend not only on those who understand and can manage high technology, but also on those who understand soil formation and retention, watershed management, and habitat for wildlife.

Implications of the Six Perspectives

The Need for Effective Collaborations Beyond the Natural Sciences

In every science, there is a tension between pursuing the most intriguing questions and the apparently most socially useful questions. The global change enterprise is currently experiencing such tension, following a period of self-determination. Government policy-makers are demanding help in drafting and implementing international environmental agreements well rooted in environmental science. Private-sector decision-makers with long time horizons—involved in such activities as natural resource extraction, coastal development, insurance, land conservancy—are demanding guidance in assessing the riskiness of investments. Natural scientists can respond by anticipating the questions that will be asked in ten years that will be answerable *then* if work is started *now*.

To give a single example, the first international agreements bearing on the management of global carbon will extend beyond fossil fuel accounting, to embrace an accounting for natural sources and sinks, only if there has been substantial progress in understanding these sources and sinks by the time these agreements are concluded. A larger accounting framework requires deeper science than is now available.

Basic environmental science is already interacting creatively with technology and policy in the clarification of the impact on stratospheric ozone of hypothetical fleets of long-range civilian aircraft flying in the stratosphere. There is a two-way flow of insights concerning stratospheric chemistry and fluid dynamics on the one hand and altitude-drag tradeoffs and nitrogen oxide formation rates in engines on the other. Each group finds its research questions in the interim results of the other.

Environmental science acquires a human face, and a more forceful mandate, when coordinated with an enterprise with human dimensions like the design of effective treaties or the evaluation of a new technology. The relationships are similar to those between biology and medicine.

To be sure, there are risks in broad collaborations and in an orientation to problem-solving. Science normally proceeds by isolating small pieces of large problems. Ecotoxicology, atmospheric chemistry, cultural studies of economic development—any of these could become paralyzed, if each subproblem were always first embedded in a system that manifested the complexity of the full problem. Or, research could suffer from becoming politicized, if stakes in particular outcomes were too deeply embedded in nominally dispassionate research. No one will be well served if the potential of good science to serve the agenda of industrial ecology is undermined by such modes of failure.

The Illusion of the Plateau

No one sees today's world as a steady state. Our focus is on change. Yet when we think a century ahead, we tend to imagine a world that has gone through a series of

transitions and has come out at a place where the pace of change has slowed—where global population, though larger, holds steady, for example. The logistic growth curve is commonly invoked—rising slowly, then rapidly, then slowly again. Those alive today are assumed to be experiencing the period of rapid change, passing through a brief phase of growth, like an adolescent on the way to maturity. Although we exult in the dynamism of our own society, how frequently our debates about the future are about the merits of alternative steady-state societies.

Will human society a century from now really resemble a steady state—with an energy mix, for example, that has not changed in the half century from 2050 to 2100 and that is not expected to change? Will people in 2100 really think of themselves as part of a world in equilibrium and like it that way, guarding against change? The economist, Herman Daly has written insightfully of steady-state economics (Daly, 1991); will he be cited as one of the visionaries of our era?

Or, might the focus in 2100 still be on change, and might public argument be closer to our own? If in 2100 nuclear fusion or renewable biomass is an important energy source, might people be arguing about whether to expand it further or to phase it out? And if in 2100 either is not playing a central role, might people be looking back wistfully at its glorious past, or be looking forward to an imminent breakthrough?

My guess is that the future in 2100 will be a no less restless time than our own. The earth system, although much better understood, will be perceived, even more than now, as a principal shaper of global human activity. A century from now, global environmental constraints will be a much stronger source of stimuli for technology and policy, and the process of accommodation will still be evolving.

I am of the transition generation, who learned the environmental facts of life only after formal education was over. Experiencing the shock of transformation of an already developed world view, my generation is particularly impatient with arguments from neoclassical economics that stress the inevitable costs of moving from one equilibrium to another and that associate every environmental improvement with a trade-off. Society is far from equilibrium. The fulcrum has shifted under the seesaw.

Industrial ecology presents an endless source of fresh questions, never before confronted, that complicate the landscape in interesting ways. Viewed from the six perspectives presented in this chapter, the near horizon provides many peaks that can be climbed, and glimpses of peaks beyond. There are no plateaus.

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