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Industrial Ecology—An Agenda for Environmental Management

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An urgent challenge facing business today is the need for technical and management approaches that will alleviate global environmental problems and support sustainable industrial growth. Industrial ecology is a new view of industrial infrastructures that is emerging in response to this challenge. It sees the patterns of the biological ecosystem as the model for solutions to environmental problems and for the future of "industrial ecosystems" that will be more compatible with the natural environment. This article discusses industrial ecology's theoretical assumptions, its implications for future environmental policy, technological developments, and practical applications for industrial reform.

OVER THE PAST several decades, we have witnessed an escalation of environmental impacts, from local environmental degradation (already the focus of much effective control activity) to adverse effects rooted in the design of the industrial infrastructure itself, with consequences that are diffused worldwide. Among the most pressing environmental challenges today is the need for a technical and management pollution prevention approach capable of responding to these problems of global scope.

Industrial ecology is emerging as a potential candidate for providing the necessary systemic response. It views industrial infrastructures as if they were a series of interlocking artificial ecosystems interfacing with the natural global ecosystem, and takes the pattern of the natural environment as a model for solving environmental problems. This represents a decisive reorientation from conquering nature—which has effectively already been done—to cooperating with it.

Policies stressing pollution control, based on the idea that the environment has an unlimited capacity to assimilate small amounts of pollutants without harm, are giving way to policies that favor pollution prevention. Ten states have already passed toxics use reduction laws that tend to emphasize closed process systems. Does this mean, by extension, that all individual industrial processes in the future should be closed systems? Questions such as these will have considerable practical significance for industry in the years ahead and are an important aspect of industrial ecology. For example, the concept of an *industrial ecosystem* exploits the transfer of industrial outputs between companies and industries in order to attain efficiencies of use and reuse. And it is possible to imagine instances in which the natural environment can act as an intermediary or carrier of industrial outputs. For instance, a net industrial producer of carbon dioxide (CO_2) at one location might be balanced by a net industrial absorber of CO_2 at another location, with the atmosphere acting as the link or transfer medium.

The time is right for the adoption of an approach of this type.

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Environmental concern is no longer a fringe preoccupation, but now enjoys broad social recognition and popular support. This, in turn, is creating the need for a means of orienting strategy, management, and technology in an emerging world of environmentally-aware business practice. As the basis for environmental strategy, industrial ecology promises to give industry the power to anticipate risk and opportunity, to provide real environmental leadership, and to engineer lasting solutions to issues of pressing social concern.

A Conceptual Model for Systemic Change

The problem of localized environmental impacts has been well understood for many years, but the scale of industrial production is now so great that even normally nontoxic emissions, like carbon dioxide, have become a serious threat to the global ecosystem. The relative scale of the industrial system is remarkable: The industrial flows of nitrogen and sulfur are equivalent to or greater than the natural flows, and for metals such as lead, cadmium, zinc, arsenic, mercury, nickel, and vanadium, the industrial flows are as much as twice the natural flows, and in the case of lead, eighteen times greater.[1]

This problem is compounded by the likely increase in scale of industrial production worldwide. All countries clearly aim to achieve the levels of material prosperity enjoyed in the West, and they intend to do it by industrializing. The combination of "scale" pollution coupled with very significant expansion of industrial activity suggests that current patterns of industrial production will not be adequate to sustain environmentally safe growth and are essentially obsolete.

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The challenge stems from the fact that we are constructing an artificial global system of chemical and materials flows within the pre-existing natural ecosystem. Logically, the solution will be an approach that allows the systems to coexist without threatening each other's viability. The most effective way of doing this is probably to model the systemic design of industry on the systemic design of the natural system. This insight is at the heart of the closely related concepts of *industrial ecology* and *industrial metabolism,* which have emerged in recent years.

The question facing industry is to understand how this thinking might function in practice and what its implementation would entail. There are many characteristic features of the natural global ecosystem that could be usefully emulated by industry:

- In the natural system there is no such thing as "waste" in the sense of something that cannot be absorbed constructively somewhere else in the system.
- Nutrients for one species are derived from the death and decay of another.
- Concentrated toxins are not stored or transported in bulk at the system level, but are synthesized and used as needed only

by species individuals.
- Materials and energy are continually circulated and transformed in extremely elegant ways. The system runs entirely on ambient solar energy, and over time has actually managed to store energy in the form of fossil fuel.
- The natural system is dynamic and information-driven, and the identity of ecosystem players is defined in process terms.
- The system permits independent activity on the part of each individual of a species, yet cooperatively meshes the activity patterns of all species. Cooperation and competition are intertwined, held in balance.

The aim of industrial ecology is to interpret and adapt an understanding of the natural system and apply it to the design of the man-made system, in order to achieve a pattern of industrialization that is not only more efficient, but also intrinsically adjusted to the tolerances and characteristics of the natural system. In this way, it will have a built-in insurance against further environmental surprises, because the essential causes of problems will remain at a fundamental level by design.

Erratum: [be eliminated]

The Business Context

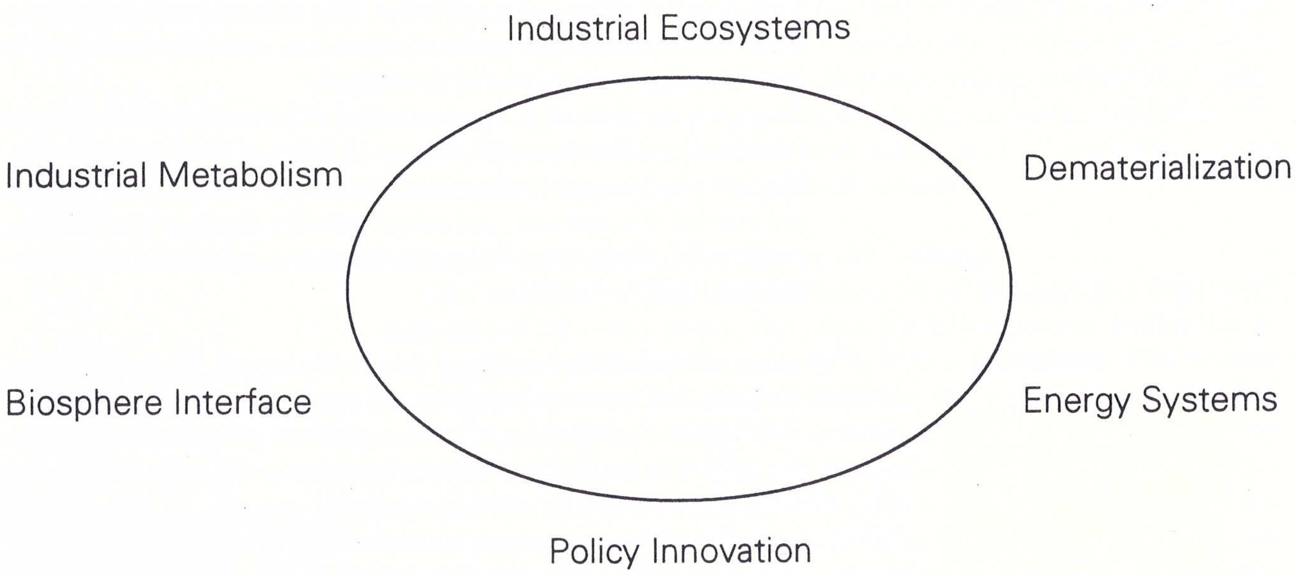
Business, in keeping with its entrepreneurial roots, is essentially forward-looking, with a preference for action and a bias toward innovation. It prefers an objective that can be clearly interpreted in management and technical terms and that is compatible with business activity. Most existing environmental analysis and commentary has not been framed to incorporate these attitudes. The intent of industrial ecology, however, is to create a common cause between industry and environmentalism. Philosophically, it is based on a set of implicit assertions:

The realization that environmental objectives can be compatible with continued technological development and wealth creation is a key element in the continuing evolution of business attitudes toward environmental issues.

- Industrial activities can be in balance with nature.
- Industrial growth with low environmental impact is possible.
- Industrial development can be made sustainable.
- Technology is an expression of fundamental human curiosity and ingenuity, thus affirming both technology and innovation, but allowing technology to be designed for improved social and environmental yield.
- Human activities are not intrinsically "unnatural."
- Today's problems can be solved only by future creativity—there is no way back.

The realization that environmental objectives can be compatible with continued technological development and wealth creation is a key element in the continuing evolution of business attitudes toward environmental issues. It comes as companies have been progressively moving from a minimal posture focused on cleaning up past mistakes

Figure 1. The Principal Elements of Industrial Ecology



to a much more active role that seeks to avoid future environmental errors.

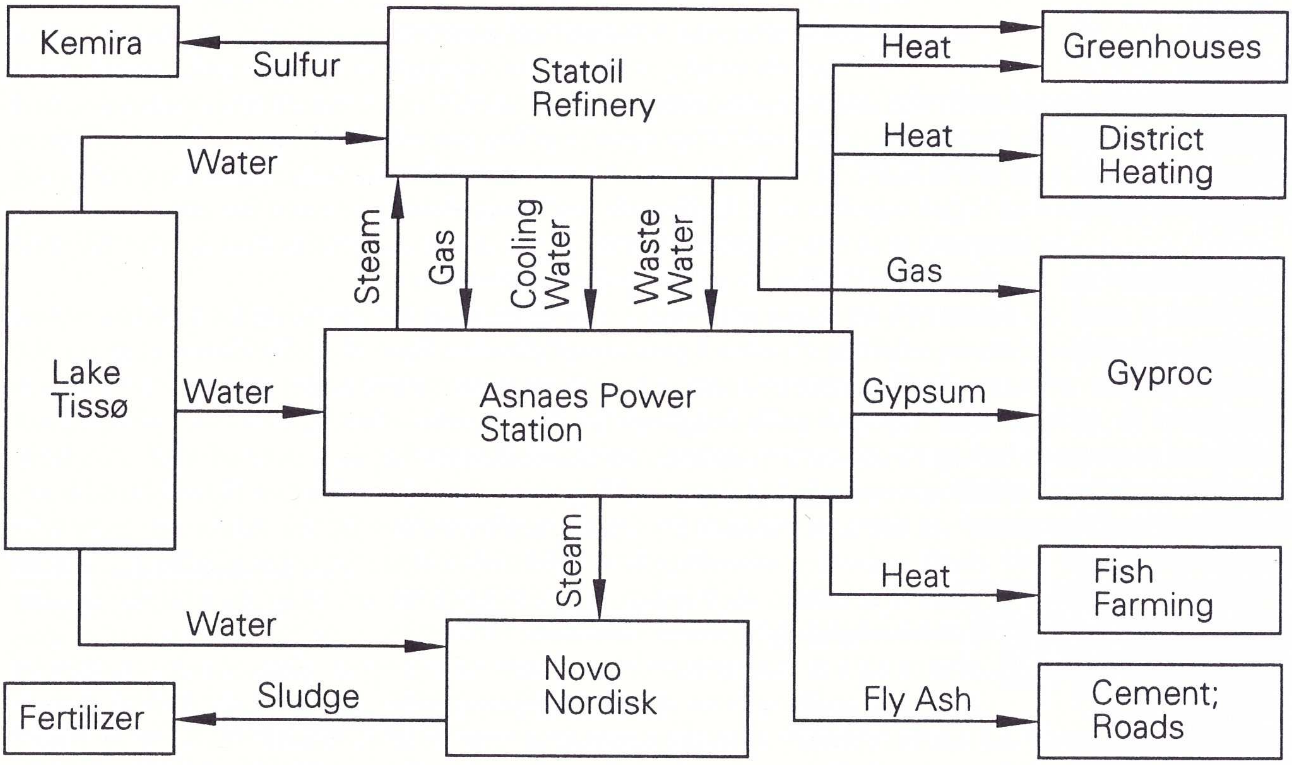
Industrial Ecology in Detail

Industrial ecology has both managerial and technological aspects. For management, it offers tools for analysis of the interface between industry and the environment, as well as a basis for developing strategic options and policy decisions. For engineering and operations, it offers a program for data gathering and technology applications. Over time, the application of industrial ecology principles to optimize relationships throughout the industrial infrastructure is likely to result in conceptual and practical advances in at least six major areas (see **Figure 1**).

The creation of industrial ecosystems

Industrial ecosystems are a logical extension of life-cycle thinking, moving from assessment to implementation. They involve "closing loops" by recycling, making maximum use of recycled materials in new production, optimizing use of materials and embedded energy, and minimizing waste generation. They also imply more than simple, one-dimensional recycling of a single material or product—as with, for example, aluminum can recycling. In effect, they represent multidimensional recycling, or the creation of complex "food webs" between companies and industries. Perhaps the key to creating industrial ecosystems is reconceptualizing wastes as products. This suggests not only the search for ways to reuse waste, but also the active selection of processes with readily reusable waste.

Figure 2. The Industrial Ecosystem at Kalundborg



Source: Novo Nordisk

A very literal example of this concept is provided by industrial environmental cooperation at the town of Kalundborg, eighty miles west of Copenhagen in Denmark,[2] that could well be a model for small and mid-sized cities in other parts of the world. The cooperation involves an electric power generating plant, an oil refinery, a biotechnology production plant, a plasterboard factory, a sulfuric acid producer, cement producers, local agriculture and horticulture, and district heating in Kalundborg (see **Figure 2**).

In Kalundborg in the early 1980s, Asnaes, the largest coal-fired electricity generating plant in Denmark, began supplying process steam to the Statoil refinery and the Novo Nordisk pharmaceutical plant. Around the same time, it began supplying surplus heat to a Kalundborg district heating scheme that has permitted the shutdown of 3,500 domestic oil-burning heating systems. Before this, Asnaes had been condensing the steam and releasing it into the local fjord. To conserve scarce fresh water, Asnaes receives cooling water and purified waste water from Statoil, and will soon use purified waste water from Novo Nordisk.

Gyproc, the wallboard producer, had been buying surplus gas from the Statoil refinery since the early 1970s, and in 1991 Asnaes began buying all the refinery's remaining surplus gas, saving 30,000 tons of coal a year. The sulfur Statoil removes from the gas, to make it cleaner-burning, is sold to Kemira, which runs a sulfuric acid plant in Jutland, Denmark. Asnaes is moving to desulfurize its smoke, and will sell 80,000 tons a year of the resulting calcium sulfate to Gyproc as "industrial gypsum"—a substitute for the mined gypsum it currently imports. In addition, fly ash from Asnaes is used for cement making and road building. (Also see "Pollution Prevention in the Electric Utility Industry" on p. 153 of this issue.)

Asnaes also uses its surplus heat for warming its own sea-water fish farm, which produces 200 tons of trout and turbot a year for the French market, and has plans to heat a thirty-seven-acre horticulture operation under glass. Sludge from the fish farm is used as fertilizer by local farmers. In addition, 330,000 tons a year of high-nutrient-value sludge from the fermentation operations at Novo Nordisk are being used as a liquid fertilizer by local farms. Although normally regarded as waste, Novo Nordisk is treating this sludge by adding chalk-lime and holding it at 90°C for an hour to neutralize any remaining microorganisms.

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It is significant that none of the examples of cooperation at Kalundborg was specifically required by regulation, and that each exchange or trade was negotiated independently. Some were based strictly on price; others were based on the installation of infrastructure by one party in exchange for a good price offered by the other. In some cases, mandated cleanliness levels—such as the requirement for reduced nitrogen in wastewater or the removal of sulfur from flue gas—have permitted or stimulated reuse of wastes, and have certainly contributed to a climate in which such cooperation became feasible. The earliest deals were purely economic, but more recent initiatives have been made for largely environmental reasons, and it has been found that these can be made to pay, too. Most of the Kalundborg exchanges are between geographically close participants; in the case of thermal transfer this is clearly important, as infrastructure costs are a factor. But proximity is not essential: The sulfur and fly ash are supplied to buyers at distant locations.

The prospect of a large-scale, and ultimately industry-wide, industrial ecosystem has been advanced by Robert Frosch and Nicholas Gallopoulos at General Motors.[3] They have given examples of industrial ecosystems involving individual materials, such as iron and steel, polyvinyl chloride (PVC), and platinum group metals. Ironically, until the advent of automotive catalytic converters in the mid-1970s, the platinum group metals were part of an extremely efficient industrial ecosystem that recycled 85 percent or more of these metals. The high value of platinum was obviously an important factor in this, but the example does indicate that impressive efficiencies can be obtained in practice. And, in many cases, apart from the savings in material costs, there can also be substantial savings in hazardous waste disposal fees.

Balancing industrial input/output and natural ecosystem capacity

Understanding and managing the interface between industry and the natural environment is an important aspect of industrial ecology, because even with industrial ecosystems there may be outputs to the natural environment that are in effect using it as a carrier or transfer medium, or as a cooperative processing component.

Management of this interface will require an expansion of knowledge about natural ecosystem dynamics on both a local and global level, detailed understanding of ecosystem assimilative capacity and recovery times, and real-time information about current environmental conditions. The capture and display of integrated environmental data will permit study of global ecosystem behavior, the monitoring of flows or point sources of pollution, and measurement of the effectiveness of interventions. As an example, the remarkable and revealing composite data images from the eight-year life of NASA's Coastal Zone Color Scanner (CZCS) satellite provided a picture of the seasonal flux of phytoplankton in the world's oceans and represented significant gains for scientific understanding of the global carbon cycle.[4]

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Rational environmental policies must be based on scientific understanding of environmental processes, and if industry is to enjoy rational policy, it has a clear interest in the development of good theory. Many questions with less than obvious answers are being generated by new scientific findings and the advance of technology. For example, as biological elements begin to be used in industrial processes following the advent of biotechnology, where exactly is the boundary between industry and the natural world? Should species be introduced deliberately into natural ecosystems in order to metabolize industrial effluents? Is there any level of industrial output that the environment can tolerate, or must emissions be reduced to zero irrespective of timing or location?

Dematerialization of industrial output

In industrially developed economies, "dematerialization"—a decline in materials and energy intensity in industrial production—is an established trend. When measured in terms of physical quantity per constant dollar of Gross National Product (GNP), basic materials use has been falling since the 1970s, and has even leveled off when measured in terms of the quantity consumed per capita. The trend to dematerialization applies not only to materials, but also applies to energy when measured in terms of energy consumed per dollar of GNP. Practical examples of this trend are the steadily declining size and increasing power of computers, or the nearly 20-percent drop in the average weight of U.S. automobiles between 1975 and 1985.[5]

The trend toward dematerialization is being driven by at least four factors:

1. The cost of producing materials has been increasing, largely because materials processing tends to be energy-intensive.
2. There is increasing competition from substitute materials, many of which are lighter and have superior properties, to basic materials such as steel. This results in actual substitution of materials with lower mass, or in the introduction of specialty versions of basic materials which give improved performance with less mass for the same function. An example is the increasing use of high-strength steels in automobile manufacture, because each kilogram of high-strength steel replaces 1.3 kilograms of standard carbon steel.[6]
3. Materials have successively saturated the markets for their bulk use. Just as the major uses of steel and cement have been in the construction of civil infrastructure (which is now essentially complete in industrialized countries), so the market for cars and consumer durables per capita is now also nearly saturated, and consists primarily of replacement demand.
4. Following on the last point, discretionary income now tends to be spent on goods and services with a lower materials content per consumer dollar, as there are no major new consumer product categories with a high materials content per dollar.

The basic trend toward dematerialization appears well-established and is clearly environmentally favorable, as it demonstrates that economic growth is becoming increasingly decoupled from growth in materials use—a fundamental issue in the "growth versus environment" debate. In effect, value is increasingly being added by emphasizing product-related information, or embedded knowledge, rather than product mass.

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Deliberate enhancement and acceleration of dematerialization in products and practices is entirely feasible. An example would be the conscious strategy by Japanese electronics manufacturers to progressively miniaturize their products. Another example would be the move by electricity-generating utilities in nineteen states in the United States to invest profitably in energy conservation as an alternative to new generating capacity. Clearly, with enough ingenuity, profitable operation of a business can be deliberately and successfully decoupled from growth in materialization.

By focusing advanced materials and design knowledge on the opportunities for radical dematerialization of basic civil infrastructure, it may even prove possible to sidestep the massive materials use that has until now been an intrinsic feature of the early stages of industrialization. A deliberate effort to develop such technologies for dematerialization could provide businesses in industrialized countries with excellent new markets in industrializing countries while at the same time making a crucial contribution to global environmental quality.

Factors running counter to dematerialization also need to be considered, however. If product quality is low (although individual product mass may be lower) products are likely to be discarded sooner, leading to increased materialization of waste. Linked with this idea is the need for increased provision for repair and recycling of products. The recent emergence of Design for Disassembly (DFD) is a response to the recognition that product design has increasingly emphasized ease of manufacture above ease of repair or recycling. (See *Pollution Prevention Review,* Winter 1991/92, for a more detailed discussion of design for disassembly). Tolerance may be needed for emerging technologies that lead to short-term increases in materialization in spite of having potential for long-term dematerialization. A case in point would be the major growth in demand for office paper caused by information technology such as desktop computers and photocopiers. Yet the "paperless office" could still become a reality with further innovations that improve the readability of computer displays and the reliability of computer memory.

Industrial ecology could introduce "materialization impact statements" or an "index of materialization" that would routinely review the materials and energy intensity of products using measures such as the power consumed in manufacturing per dollar of product value. We may come to regard kilowatt hour per dollar, or kilo per dollar, as an important attribute of new products we are planning to buy.

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Improving the metabolic pathways of industry

In addition to the concept of industrial ecosystems, which try to ensure that all industrial outputs are folded back into the system, it is likely that paying attention to the closely related concept of "industrial metabolism"[7] (chemical and material transformations) will also yield significant environmental benefits.

Systematic study of the type and pattern of chemical reactions and materials flows in the industrial system indicates a number of potential areas of improvement. Almost all industrial processes are fossil-fueled and often involve high temperatures and pressures. They also tend to involve multiple separate steps, in which the intermediate metabolites are incorporated into the next production stage, or released as wastes, rather than being reused. In addition, many of the end uses of materials can be dispersed into the environment as they are used, with no hope of recovery for recycling.[8] Car and truck brake pads and tires, for example, leave a finely distributed powder on highways as they wear down. This is of particular concern when toxic heavy metals are involved.

Compared with the elegance and economy of biological metabolic processes such as photosynthesis, or the citric acid cycle, most existing industrial processes appear to be far from their potential ultimate efficiency in terms of the basic chemical and energy pathways they use. This suggests that biotechnology may offer the promise of radically improved industrial process pathways, perhaps able to move from primary feedstocks to final products in a single step. A simple example of the replacement of a mechanical process by a biological process is the established bacterial processing of metal ore, which has allowed extraction from mine tailings that were previously uneconomic to process.[9]

Minnesota Mining and Manufacturing Company (3M) provides an excellent example of the industrial metabolic improvement approach in practice: its frequently cited Pollution Prevention Pays, or 3P, Program. 3P encourages technical innovation to prevent pollution at the source through four methods: product reformulation, process modification, equipment redesign, and resource recovery. Projects eligible for recognition under 3P use one of these methods to eliminate or reduce pollution, save resources and money, and advance technology or engineering practice. Over fifteen years, 3P projects have reduced worldwide releases of pollutants from 3M operations by half a million tons a year.

The ideal end-point of improved industrial metabolism would be advances across the spectrum of industrial processes, bringing them more into line with the metabolic patterns used in the natural ecosystem. In-process energy demands would be reduced, processes would be safer, and industrial metabolites would be more compatible with natural ecosystems. This is undoubtedly a longer-term objective, but even in the form of incremental process improvements, industrial metabolism has much to offer as a way of thinking about the environmental compatibility of industrial processes.

A global, systemic, environmentally-oriented approach to energy technology and supply infrastructures is . . . a high priority of industrial ecology.

Systemic patterns of energy use

Energy is the life-blood of industrial activity. The extraction, transportation, processing, and use of energy sources account for the largest environmental impacts of the industrial system. A global, systemic, environmentally-oriented approach to energy technology and supply infrastructures is, therefore, a high priority of industrial ecology.

Existing patterns of energy sourcing and distribution are unsustainable, both in terms of pollution and because fossil energy resources are finite. Moreover, whenever energy is released in the global ecosystem in excess of the ambient energy load, it amounts to stress that the system has to absorb. The current prospect of global warming illustrates what may happen as a result.

The use of carbon-containing fossil fuels is at the heart of the problematic release of the greenhouse gas CO_2, and a good part of the associated global warming problem. Every ton of carbon in fuel combines with oxygen in the atmosphere to release 3.66 tons of CO_2. But the amount of carbon in fossil fuel varies significantly. Expressed as the proportion of carbon to hydrogen, fuel wood is roughly 91 percent carbon, coal 50 percent, oil 33 percent, and natural gas 20 percent.[10] What is interesting about these ratios is that the fuels used as the industrial system has evolved have become increasingly hydrogen-rich. In fact, in theory at least, pure hydrogen would be the ideal clean fuel. When it burns, it releases only water vapor as it combines with oxygen in the atmosphere.[11]

This attractive characteristic has led to the concept of a future "hydrogen economy." Although formidable hurdles need to be overcome for practical development, this scenario could represent the ultimate environmental energy supply infrastructure. The hydrogen would be produced from water using heat or electricity, with the energy for this being supplied by solar or hydro power (it could also be supplied by nuclear power). The hydrogen would then be transferred by pipeline to its point of use, acting as a much more efficient energy carrier than electric power grids, and having the advantage that it can be used as fuel by conventional internal-combustion engines.

Under this scenario, there would initially be a high energy cost to construct the necessary pipeline, transport, and storage infrastructure, and to manufacture and install the long-life ambient energy capture devices such as photovoltaics or solar thermal collectors. This energy could be provided by fossil fuel in what would amount to a transfer from our energy "capital" account in the earth's crust to another form of energy supply "capital"—an ambient energy infrastructure.

This may not represent the final shape of the energy supply infrastructure of the future, but it does illustrate the systemic thinking that is required.

If industrial ecology is to achieve its full impact, it will need to be backed up by innovative new policies that coherently align financial, economic, and regulatory scorekeeping on an international basis.

Aligning policy with long-term industrial evolution

If industrial ecology is to achieve its full impact, it will need to be backed up by innovative new policies that coherently align financial, economic, and regulatory scorekeeping on an international basis. There are a variety of policy issues that need to be addressed in order to do this. The real question now is what form the full range of these initiatives will take, when and how they will be applied, and with what degree of consistency across jurisdictions.

The primary policy concern is how to reflect environmental damage in economic and financial accounting. Such damage is currently referred to as a negative "externality" because it is external to economic accounting, and therefore regarded as free of cost by the market. There are at least two basic mechanisms being proposed for this direct transfer of environmental costs into the market domain. The first is the imposition of green taxes, such as the tax on CFCs following the Montreal Protocol, or the concept of a carbon tax to counter the release of carbon dioxide.

An alternative approach would be for governments to issue a finite number of pollution permits of various types, which could be bought and sold in the market, creating a financial incentive to reduce pollution. To reduce the sum total of pollution, the pool of credits would be progressively reduced over time. The U.S. Environmental Protection Agency (EPA) successfully used this approach during the phaseout of leaded gasoline in the United States, and is currently using it in Los Angeles in a program called "emissions trading."

Not only does the market not see the hidden cost of environmental damage, but it undervalues environmental capital by applying market interest rates when making decisions about the use of natural resources. If a forest growing at 2 percent or 3 percent a year is compared with a lumber mill that will earn, say, a 15-percent return on investment, the market is likely to sacrifice the forest to feed the mill. As a result, it has been suggested that the discount rates used when making "present value" decisions about environmental assets should reflect natural growth or ecosystem recovery rates.

The scorecard used to measure the performance of national economies is Gross National Product (GNP), yet this allows no depreciation for depleted or damaged natural resources, and is increasingly coming under fire for being an inadequate measure of national prosperity. A number of alternatives or supplements have been proposed that would provide a more balanced picture. The United Nations Development Program (UNDP) has proposed a supplementary Human Development Index (HDI), and World Bank economist Herman Daly has calculated an "Index of Sustainable Economic Welfare" (ISEW), which accounts for a variety of environmental deficits.

All these policy options, and others, will benefit by being viewed from the systemic perspective that industrial ecology can provide. It is likely that an analysis based on industrial ecology will prove to be the most effective way both of discriminating between policy options and of achieving an integrated policy platform for the environment.

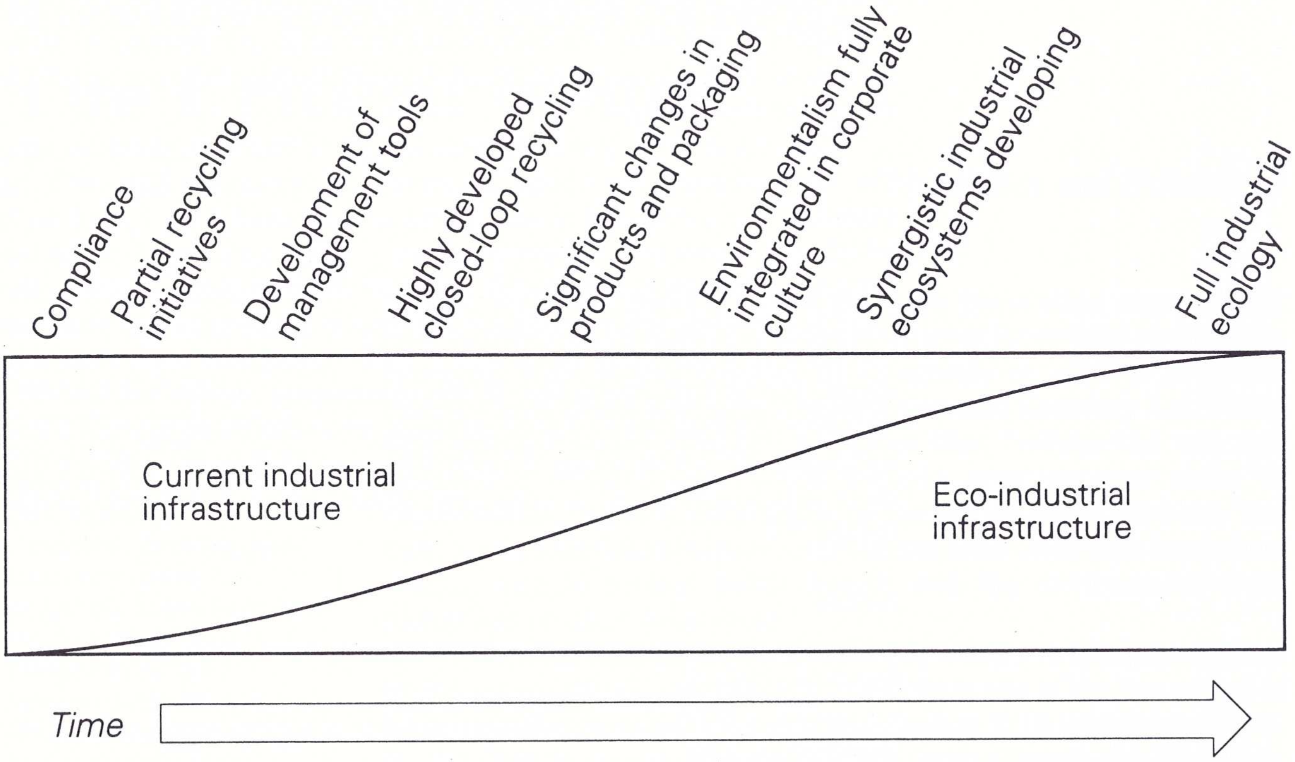
Future Developments

It is likely that there will be not just one class of industrial ecosystems, but an entire spectrum of ecosystems. These would run from single material ecosystems, such as the recycling system for aluminum beverage cans, through a variety of more complex industrial ecosystems and hybrid bio-industrial ecosystems, to original natural ecosystems. To give this perspective, we should remember that human modification and manipulation of ecosystems is as old as agriculture. The challenge we face now is the need to integrate industry into the equation, and consciously to design a world that is both aesthetically pleasing, biologically stable, and economically productive.

In the future, the scale of our activities is likely to be so great, and arguably is already, that no part of the world will remain entirely unaltered by industrial development.

In the future, the scale of our activities is likely to be so great, and arguably is already, that no part of the world will remain entirely unaltered by industrial development. As a result, it will not be possible to define natural ecosystems, or nature itself, simply by referring to "what is out there." We will need to define, along many dimensions, the parameters of what is valuable in a natural system,

Figure 3. The Emergence of an Industrial Infrastructure



so that we can monitor and regulate the degree of impact we have on it, and have a basis for restoring it if necessary.

The result of an industrial ecological approach over time will be an overall transition to an eco-industrial infrastructure (see **Figure 3**), so that all process systems and equipment, and plant and factory design, will eventually be designed to interconnect with industrial ecosystems as a matter of course. Older, linear flow concepts of design will be considered obsolete, and a dominant new generation of technology will have come into being, characterized not necessarily by the novelty of its principles, but by its ability to interlock with other parts of an industrial ecosystem. To a great extent, the industrial leaders of tomorrow will be those who now recognize the conceptual logic of this new approach to technology and invest in the R&D to achieve it.

Conclusion

The concept of industrial ecology may at first appear impractical or overly idealistic, but it is almost certainly the most plausible model for the industrial-environmental nexus of the future. Individual researchers at organizations as diverse as AT&T Bell Laboratories, Carnegie-Mellon University, Princeton University's Center for Energy and Environmental Studies, and General Motors are actively studying or promoting the concept. In addition, major corporations that are environmental leaders are in effect already beginning to put industrial ecology into practice. Its component elements are evident in their policies and practices, even though these companies may not explicitly recognize the concept.

Industry is rapidly moving into an era of new values concerning the environment, in which corporate environmentalism will be essential for profitability and business survival. The speed with which a corporation understands and addresses these changing norms and values will define a large part of its competitive edge in the future.[12] The benefit offered by industrial ecology is that it provides a coherent framework for shaping and testing strategic thinking about the entire spectrum of environmental issues confronting industry. Executives and policymakers who take steps to absorb and appreciate this new mode of thinking now will find themselves and their organizations at a very real advantage in the world of the future.[13] ◆

Notes

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4. Lewis, Marlon R., "The Variegated Ocean: A View from Space," *New Scientist* (October 7, 1989), 37-40.

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7. Ayers, Robert U., *Industrial Metabolism in Technology and Environment,* edited by Jesse H. Ausubel and Hedy E. Sladovich (Washington, DC: National Academy Press, 1989), 23-49.

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9. Debus, Keith H., "Mining with Microbes," *Technology Review* (August-September 1990), 50-57.

10. Lee, Thomas H., *Advanced Fossil Fuel Systems and Beyond in Technology and Environment,* edited by Jesse H. Ausubel and Hedy E. Sladovich (Washington, DC: National Academy Press, 1989), 126.

11. Hydrogen also produces small amounts of nitrogen oxides (NOx) if burned at high temperatures in air.

12. Choucri, Nazli, "The Global Environment & Multinational Corporations," *Technology Review* (April 1991), 52-59.

13. For more information, please contact the author at Global Business Network, 5900-X Hollis Street, Emeryville, CA 94608. Telephone: 510-547-6822.