



# Industrial Ecology

An Environmental Agenda for Industry

Hardin Tibbs



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### ***Foreword***

This paper focuses on industrial ecology, a subject just emerging as a distinct discipline. Although still in its early stages, it shows promise as an effective framework for addressing and integrating the very wide range of environmental issues facing both business and government today. While the practical implementation of this thinking lies some way in the future, the overview presented here should be of considerable interest to all those with a professional involvement in environmental management and environmental policy-making.

The author of this paper, Hardin Tibbs, is a senior staff member of Global Business Network.

### ***The Cover***

The cover image shows a Mobius strip, formed by making a loop with a single twist in it. Its special property is that it has only one surface—a line drawn along it will ultimately return to its starting point, having travelled the full length of both “sides” of the paper.

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# Industrial Ecology: An Environmental Agenda for Industry

## Managing for the Global Environment—a Complex Challenge

Operating on a global scale brings problems at a global level. The environmental issues now facing industry are no longer focused simply on local toxic impacts—although these remain potentially serious. There are now unintended effects on the total global environment, of which global warming and ozone depletion may be only the most visible of a multitude of adverse symptoms.

The emerging environmental challenge requires a technical and management approach capable of addressing problems of global scope. By contrast, the environmental agenda of companies today is frequently driven by a list of individual issues because there is no accepted overall framework to shape comprehensive programs.

Corporate environmental agendas typically list goals such as eliminating the use of chlorofluorocarbons (CFCs), promoting recycling, increasing energy efficiency, and minimizing the production of hazardous waste. The question is whether this kind of action list goes far enough in dealing with underlying causes, or whether it is largely treating symptoms. Will it protect business against further “environmental surprises?” In its complexity, the global environmental problem-set somewhat resembles an iceberg—well-publicized environmental problems are the visible one-tenth above the surface. We still know too little about the adaptive capacity of the natural environment as a whole to predict confidently how it will react to continuing industrialization. If the iceberg suddenly rolls over, it could expose problems that the average business is quite unprepared for.

Effective defense against this uncertainty will be based on the recognition of a key principle. The ultimate driver of the global environmental crisis is industrialization, which means significant, systemic industrial change will be unavoidable if society is to eliminate the root causes of environmental damage. The resulting program of business change will have to be based in a far-sighted conceptual framework if it is to ensure the long-term viability of industrialization, and implementation will need to begin soon.

The aim of this paper is to introduce and discuss the concept of industrial ecology as the best available candidate for this needed conceptual framework. In essence, industrial ecology involves designing industrial infrastructures as if they were a series of interlocking man-made ecosystems interfacing with the natural global ecosystem. Industrial ecology takes the pattern of the natural environment as a model for solving environmental problems, creating a new paradigm for the industrial system in the process. This is “biomimetic” design on the largest scale, and represents a decisive reorientation from conquering nature—which we have effectively already done—to cooperating with it.

The time is right for the adoption of such an approach. Environmental concern is no



*Industrial ecology involves designing industrial infrastructures as if they were a series of interlocking ecosystems.*

longer a fringe preoccupation, but now enjoys broad social recognition and popular support. Government environmental legislation is becoming increasingly stringent, and the media frequently act as environmental proponents in reporting environmental damage. As a result, major companies are beginning to react with what has been called “corporate environmentalism.” And 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.

*The move to worldwide industrialization means that current patterns of industrial production are all but obsolete.*

## A Conceptual Model for Systemic Change

The problem of localized environmental impacts has been well understood for many years, and industry and regulatory authorities have evolved procedures for minimizing classic environmental problems such as local emission of toxic pollutants. 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. Seen in its broadest terms, the problem for our industrial system is that it is steadily growing larger in comparison with the natural environment, so that its outputs are reaching levels that are damaging because of their sheer volume, regardless of whether they are traditional pollutants or not. 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, 18 times greater.<sup>1</sup> The natural environment is a brilliantly ingenious and adaptive system, but there are undoubtedly limits to its ability to absorb vastly increased flows of even naturally abundant chemicals and remain the friendly place we call home.

The scale of industrial production worldwide seems set for inexorable growth. All countries clearly aim to achieve the levels of material prosperity enjoyed in the West, and they intend to do it by industrializing. Since their wish represents market growth to western companies, and is directly in line with current democratic and economic rhetoric, it seems politically inevitable. Indeed, leaving aside environmental concerns, simple equity argues that it is also morally unavoidable. We are witnessing the evolution of a fully industrialized world, with global industrial production, global markets, global telecommunications highways, and global prosperity. This prospect brings the realization that current patterns of industrial production will not be adequate to sustain environmentally safe growth on such a scale and are therefore all but obsolete.

The challenge stems from the fact that we are constructing an artificial global system within a preexisting natural one. It is easy to forget that the industrial system as a whole, as it is now structured, depends on a healthy natural global ecosystem for its functioning. While the industrial system was small, we regarded the natural global ecosystem as limitlessly vast. As a result we treated the functioning of the natural system as irrelevant to our industrial operations. But the continuing expansion of the worldwide industrial system will oblige us to reconsider this view.

The solution will be an approach that allows the two systems to coexist without threatening each other's viability. Nature is the undisputed master of complex systems, and in our design of a global industrial system we could learn much from the way the natural global ecosystem functions. In doing so, we could not only improve the efficiency of industry but also find more acceptable ways of interfacing it with nature.

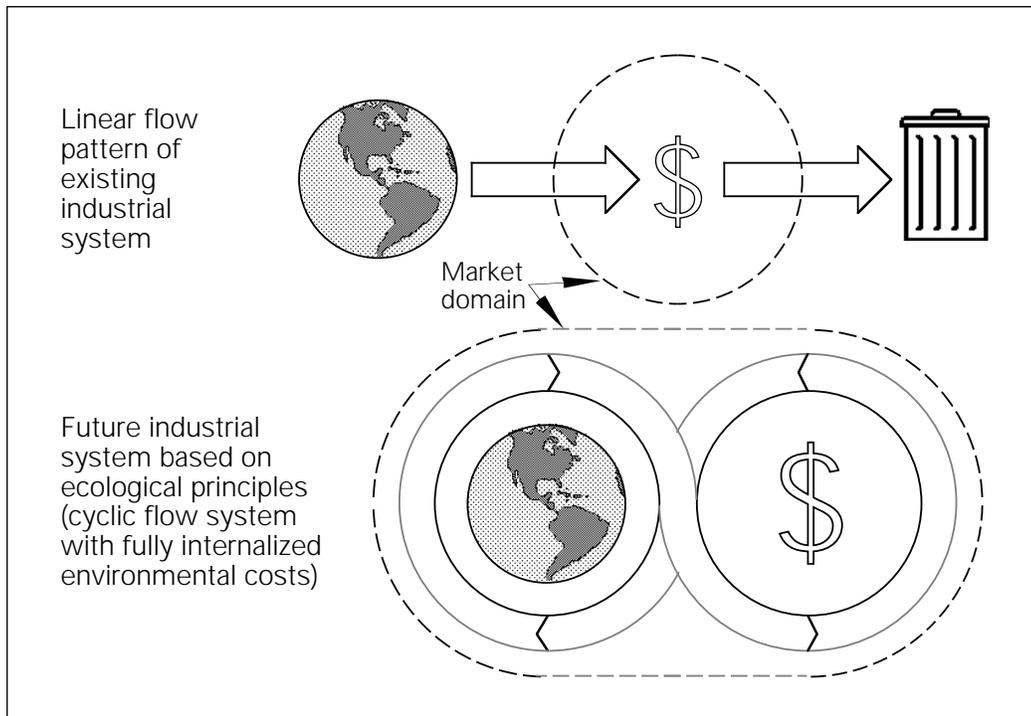


Figure 1:  
Economic value  
generation and the  
underlying pattern of  
materials flow

Indeed, 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, industrial ecosystems, industrial metabolism, and industrial symbiosis, all of which have been emerging in recent years. The question facing industry is to understand how this thinking might function in practice, and what implementation would involve.

At the moment, the industrial “system” is less a system than a collection of linear flows—drawing materials and fossil energy from nature, processing them for economic value, and dumping the residue back into nature (see Figure 1). This “extract and dump” pattern is at the root of our current environmental difficulties. The natural environment works very differently. From its early non-cyclic origins, it has evolved into a truly cyclic system, endlessly circulating and transforming materials, and managing to run almost entirely on ambient solar energy. There is no reason why the international economy could not be reframed along these lines as a continuous cyclic flow of materials requiring a significantly lower level of energy input, and a vastly lower level of raw materials input from, and waste output to, the natural environment. Such a “cyclic economy” would not be limited in terms of the economic activity and growth it could generate, but it would be limited in terms of the input of new materials and energy it required.

There are many characteristic features of the natural global ecosystem that could usefully be 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. (An example: carbon dioxide exhaled by animals is absorbed by plants as a “feedstock” for photosynthesis.)

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The challenge now is to engineer industrial infrastructures that are good ecological citizens, so that the international demand for industrialization can be met.

- Life-giving nutrients for one species are derived from the death and decay of another. (Bacteria and fungi in soil break down animal and plant wastes for use by growing plants.)
- Concentrated toxins are not stored or transported in bulk at the system level, but are synthesized and used as needed only by the individuals of a species. (Snake venom is produced in glands immediately behind the snake's teeth.)
- 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 cycling of nitrogen from the atmosphere into protein and back again to the atmosphere is accomplished by an intricate chain of bacterial, plant and animal metabolism.)
- The natural system is dynamic and information-driven, and the identity of ecosystem players is defined in process terms. (The metabolic and instinctive activity of species is coded in their DNA and shapes much behavior in ecosystems, which can be viewed as systems for transforming chemicals and energy.)
- 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 interlinked, held in balance. (The behavior of species in ecosystems is modified in an interactively choreographed flow of responses to the availability of food, variations in seasonal climate, the immigration of new species, etc. Competition for food resources is often minimized by "timesharing" or niche adaptation.)

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 which is intrinsically adjusted to the tolerances and characteristics of the natural system. The emphasis is on forms of technology that work *with* natural systems, not *against* them. An industrial system of this type will have built-in insurance against environmental surprises, because their underlying causes will have been eliminated at the design stage.

Our industrial system ultimately depends on the natural ecosystem because it is embedded within it. Our challenge now is to engineer industrial infrastructures that are good ecological citizens so that the scale of industrial activity can continue to increase to meet international demand without running into environmental constraints, or, put another way, without resulting in a net negative impact on the quality of life.

### The Business Context—"Corporate Environmentalism"

The backdrop to industrial ecology is a history of environmental debate spanning two decades or more. Basic environmental awareness was established by the late 1960s, following publication of books such as Rachel Carson's *Silent Spring*,<sup>2</sup> and began to attract serious academic attention in the 1970s. The application of computer modelling to environmental issues resulted in the *Limits to Growth*<sup>3</sup> study for the Club of Rome, and the *Global 2000 Report*<sup>4</sup> to President Carter, which it inspired in the early 1980s. The essential conclusions of these reports were that unchecked industrial growth would

inevitably lead to significant worldwide environmental degradation, and that serious consideration must therefore be given to curtailing industrial growth.

This point of view was not without its critics: the most vocal and cogent of these was probably Herman Kahn, who, in his book *The Resourceful Earth*,<sup>5</sup> coauthored with Julian Simon, refuted the idea that the earth is as fragile environmentally or as limited in resources as the earlier analyses had assumed. The need for some environmental caution was accepted, but it was argued that the level of public concern was already at a level fully adequate to ensure a corrective business response. Indeed, it was argued, any extra governmental action on the environment—in the form of added regulatory burden—ran the risk of weakening the long-term health of the economy and detracting more from future wealth and quality of life than would the postulated environmental deterioration.

Elements from both poles of the argument appear to be converging into a commitment to action. Industry increasingly accepts the environmental imperative, and has many programs in place to repair the environmental mistakes of the past. Environmental regulations have proliferated to become a mature and formidable body of legislation. The prospect of radical energy efficiency through new technologies has demonstrated that further economic growth may indeed be compatible with environmental stability.

At the same time, as is made clear in the recently published book *Beyond the Limits*,<sup>6</sup> written by the original *Limits to Growth* authors, current levels of industrial throughput are now seriously eating into the environment's ability to replenish natural biological stocks and neutralize pollution. And there is generally acknowledged evidence of serious systemic environmental damage, which only threatens to get worse. In other words, there actually is an environmental problem, and there is general agreement that something needs to be done about it. The difficulty is that environmental debate so far has been focused on making a case for environmentalism, or arguing against it, and has not provided industry with a clear agenda for positive environmental response.

An effective environmental agenda will be one that industry can align with easily. In contemplating significant change, business needs to be able to find common ground with the program of action being proposed. Business, in keeping with its entrepreneurial roots, is essentially optimistic and forward looking, with a preference for action and a willingness to accept measured risk. It has a bias toward innovation, and a desire for independence and leadership. It also prefers an objective that can be clearly interpreted in management and technical terms, and is compatible with business activity. The ideal agenda should allow progress to be measured, enhance business performance, and be applicable in any industry, permitting alliances and cooperation among corporations and between industries.

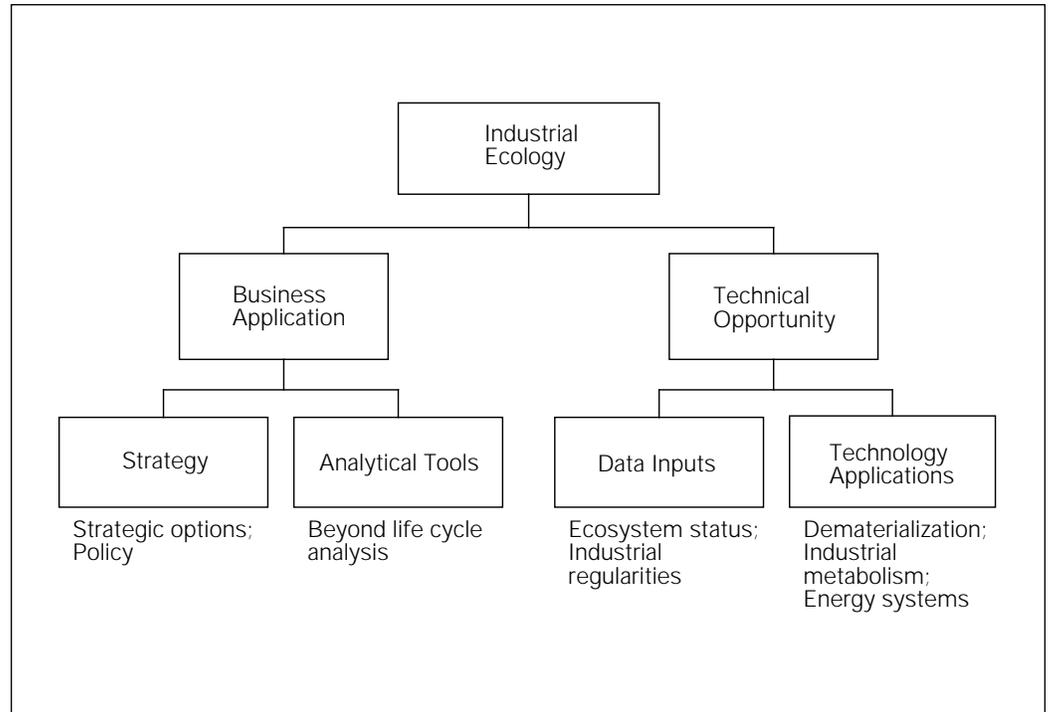
Most existing environmental analysis and commentary has not been framed to incorporate these attitudes, but the intent of industrial ecology is to create a common cause between industry and environmentalism. Philosophically, it is based on a set of implicit assertions:

- With appropriate design, industrial activities can be brought into balance with nature, and industrial growth with low environmental impact is possible. As a result, we have the ability to make industrial development sustainable in the long term, but to do so we must actively apply the appropriate policies and technologies.



*An effective environmental agenda will be one that industry can align with easily.*

**Figure 2:**  
**Industrial ecology**  
**permits an integrated**  
**managerial and**  
**technological**  
**interpretation**

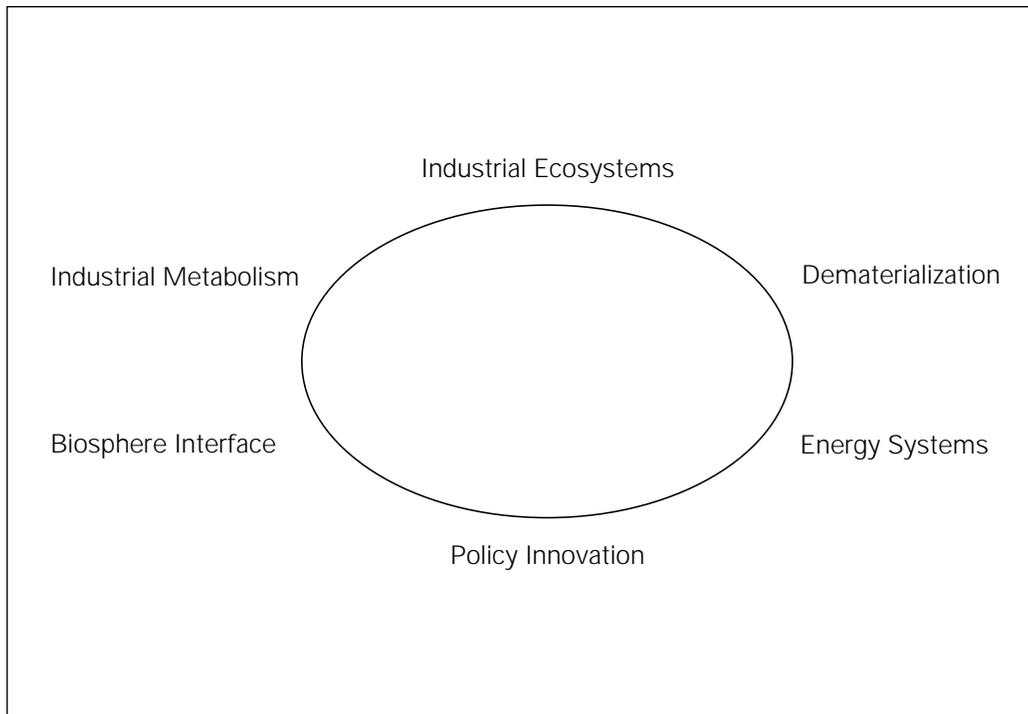


*Industrial ecology implicitly asserts that industrial development can be made sustainable by decoupling environmental impact from economic growth.*

- Technology itself is simply an expression of fundamental human curiosity and ingenuity. It is no more intrinsically “unnatural” than human beings themselves and would merely be reinvented if we tried to get rid of it. This view affirms both technology and innovation, but introduces the idea that technology can be designed for improved social and environmental yield, since it is shaped by human decisions.
- Today’s problems are so complex they can only be solved by the creation of future newness—there is no “way back” to a supposedly better earlier time. For instance, if we chose to stop all use of nuclear power, the simple need to keep existing radioactive waste safe would require that we retain nuclear know-how indefinitely into the future.

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

Initially, business had a hard time taking environmentalism seriously, and saw the philosophy underpinning it as passive, regressive, anti-growth, and anti-technology—an attitude that made genuine action on environmental issues almost impossible. In the terminology of strategic planning, the resulting posture was purely reactive. Any environmental action taken was largely in response to the pressure of legislation or public opinion. In its narrowly-defined desire to defend the status quo and to remain profitable, the company of yesterday restricted itself to the minimum effort necessary to ensure compliance and end-of-pipeline cleanup. This posture was intrinsically vulnerable to unanticipated risks and unforeseen costs, and suffered from an inability to acknowledge new business opportunities being created by environmental concern.



**Figure 3:**  
The principal elements  
of industrial ecology

The emerging “green corporation,” on the other hand, accepts the environmental imperative and willingly assumes the mantle of environmental leadership. It adopts a truly “proactive” strategic posture, favoring voluntary product and process redesign, as well as the avoidance of pollution and waste, and welcoming cooperation and alliances with other organizations. In short, it takes the long-term view and addresses environmental issues by attacking their root causes. This new outlook has been aptly termed “corporate environmentalism,” and is founded on the recognition that environmentalism can be compatible with good business and is essential for business survival.

Industrial ecology gives structure and consistency to emerging corporate environmental conviction. As a framework for environmental strategy, industrial ecology is uniquely able to provide the coordinating vision for effective management planning and technical implementation in tomorrow’s green corporation. It may even evolve into an intellectual platform that will frame public environmental debate. 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.

### Industrial Ecology in Detail

Applied industrial ecology is an integrated management and technical program (see Figure 2). On the management side, it offers tools for analysis of the interface between industry and the environment, and provides a basis for developing strategic options and policy decisions. The analytical tools go beyond existing Life Cycle Analysis (LCA) methods, to the detailed mapping of existing industrial ecosystems and the patterns of industrial metabolism within industrial processes. These new methods are described in the sections that follow.

*The emerging “green corporation” willingly assumes the mantle of environmental leadership.*

On the technical side industrial ecology offers specific engineering and operational programs for data gathering, technology deployment and product design. The techniques and technologies of real-time environmental monitoring are becoming increasingly sophisticated, and will be integrated using information technology as a practical tool for mapping and managing environmental impacts. Process and product design will reflect industrial ecology thinking from initial design principles to final decommissioning and disassembly.

Over time, the application of these new tools and techniques will lead to conceptual and practical advances in at least six areas (see Figure 3):

Industrial ecosystems represent “multidimensional” recycling—the creation of industrial “food webs.”

### **1 • The creation of industrial ecosystems**

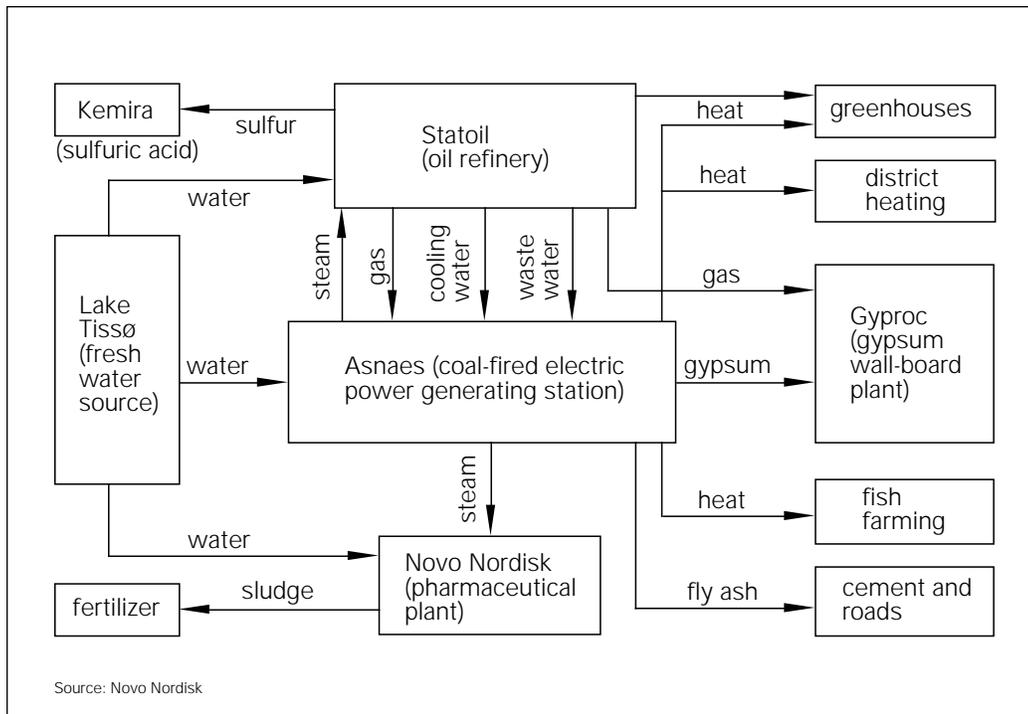
Industrial ecosystems are a logical extension of life-cycle thinking, moving from assessment to implementation. They involve “closing loops” by recycling, making maximum use of recycled materials in new production, optimizing use of materials and embedded energy, minimizing waste generation, and reevaluating “wastes” as raw material for other processes. They also imply more than simple “one-dimensional” recycling of a single material or product—as with, for example, aluminum beverage can recycling. In effect, they represent “multidimensional” recycling, or the creation of complex “food webs” between companies and industries.

A very literal example of this concept is provided by industrial environmental cooperation at the town of Kalundborg, 80 miles west of Copenhagen in Denmark.<sup>7</sup> 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 4).

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 shut-down of 3,500 domestic oil-burning heating systems. Before this, Asnaes had been condensing the steam and releasing it into the local fjord. Fresh water is scarce in Kalundborg and has to be pumped from lake Tissø some seven or eight miles away, so water conservation is important. Statoil supplies cooling water and purified waste water to Asnaes, which will soon also use purified waste water from Novo Nordisk.

Gyproc, the wallboard producer, had been buying surplus gas from the 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. This initiative was possible because Statoil began removing the excess sulfur in the gas, to make it cleaner-burning. The removed sulfur is sold to Kemira, which runs a sulfuric acid plant in Jutland. Asnaes is also moving to desulfurize its smoke, using a process that yields calcium sulfate as a side product. 80,000 tons of this a year will be sold 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.

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. Sludge from the fish farm is used as fertilizer by local farmers. Asnaes has more surplus heat available,



**Figure 4:**  
The flow of resources and by-products between participants in the pioneering industrial ecosystem at Kalundborg in Denmark

and there are plans to use it for a 37 acre horticulture operation under glass. 330,000 tons a year of high nutrient-value sludge from the fermentation operations at Novo Nordisk are also being used as a liquid fertilizer by local farms. This type of sludge is normally regarded as waste, but Novo Nordisk is treating it by adding chalk-lime and holding it at 90°C for an hour to neutralize any remaining microorganisms.

It is significant that none of the examples of cooperation at Kalundborg was specifically required by regulation, and that each exchange or trade is negotiated independently. Some were based strictly on price, while 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 waste water, 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. At Kalundborg, the pattern of cooperation is described as “industrial symbiosis,” but it seems more appropriate to consider it as a pioneering industrial ecosystem, since symbiosis usually refers only to cooperation between two organisms. 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.

Perhaps the key to creating industrial ecosystems is to reconceptualize 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. This can start with just a single process or waste. As an example, Du Pont used to dispose of hexamethyleneimine (HMI), a chemical generated during the production of nylon. But when it started

*The earliest deals at Kalundborg were purely economic, but more recent initiatives made for environmental reasons have been made to pay, too.*

looking for alternatives to disposal, it was able to find a very successful market in the pharmaceutical and coatings industries.

The prospect of a large-scale, and ultimately industry-wide industrial ecosystem has been advanced by Robert Frosch and Nicholas Gallopoulos at General Motors.<sup>8</sup> 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.

Management of the interface between industry and the natural environment will require an expansion of knowledge about natural ecosystem dynamics.

## **2 • Balancing industrial input and output to natural ecosystem capacity**

The thrust of industrial ecology is to avoid industrial stress on the environment. There will nevertheless be many points of contact between industry and the environment, and 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 in the industrial ecosystem.

Industrial ecology will therefore be concerned with management of the interface between industry and the natural environment. This will require an expansion of knowledge about natural ecosystem dynamics on both a local and a global level, detailed understanding of ecosystem assimilative capacity and recovery times, and real time information about current environmental conditions. It will involve studying ways that industry can safely interface with nature, in terms of location, intensity, and timing, and developing means of continuously adjusting these in response to real time feedback about environmental conditions. It must also involve concern about the risk of catastrophic failure of industrial operations, stressing design that is intrinsically incapable of acute environmental impact—much as current design approaches to nuclear fission reactors stress fail-safe cooling principles and low radioactive fuel medium concentrations that are immune to meltdown (although these still have not solved the problem of radioactive waste accumulation).

Efforts to establish continuous real-time monitoring of environmental conditions have already begun, as have attempts to weave these together on a global scale, using advanced computer technologies, to create a seamless real-time picture of planetary ecosystem functioning. An awareness of the importance of this can be seen in Tom Van Sant's GeoSphere Project, the creation of a single database of satellite images that reveal a cloud-free picture of the earth's entire surface—over which an overlay of real-time weather patterns will be created. Similarly, the impact of NASA's graphic images of stratospheric ozone depletion over the antarctic played a leading role in consolidating political support for CFC restraint.

Less well known are the equally remarkable and revealing composite data images from the eight-year life of NASA's Coastal Zone Color Scanner (CZCS) satellite. These remarkable pictures have provided a picture of the seasonal flux of phytoplankton in the world's oceans, with significant gains for scientific understanding of the global carbon cycle.<sup>9</sup> NASA's Upper Atmosphere Research Satellite (UARS) is expected to provide a similar gain in understanding atmospheric processes. The value of this kind of

data has prompted the ambitious “Mission to Planet Earth” proposal by NASA, which would place an array of environmental monitoring satellites in orbit during the 1990s.

A pioneering example of the corporate use of information technology to integrate environmental, technical, and management data is provided by Johnson & Johnson (J&J), the international health-care products manufacturer. Its innovative emergency management software, “Emergency Information System/Chemicals” (EIS/C), combines three elements: data, communications technology, and an electronic mapping capability that allows the company to show its facilities in detail, down to the floor plans of individual buildings and precise locations of regulated chemicals. It can also access regulatory, chemical, and emergency response data about hazardous materials by drawing on J&J’s “PC-Based Regulatory, Environmental, Chemical Information System” (PRECIS).<sup>10</sup>

EIS/C’s maps depict not only the J&J facilities and the location of chemicals, but also show the surrounding community, including the location of schools, hospitals, transportation systems and so on, and can “zoom” out to show the country and its regional location. The system is also capable of collecting local meteorological data real-time, and can use this to plot predicted dispersion plumes of any airborne chemicals, displaying them on the local area maps. During hazardous chemical emergencies, local authorities often have difficulty pinpointing where the accident has occurred, what other chemicals are stored on site, and other vital information needed for an effective response to the accident. For this reason, J&J has donated the EIS/C software, as well as personal computers or the funds to purchase them, to local emergency management authorities including fire fighters and police. In this way, it has prepared both itself and the local communities where it operates for potential chemical emergencies. As of 1991, EIS/C has been pilot-tested at eight sites in New Jersey as well as several sites in Portugal, Belgium, and the U.K., and will eventually be used worldwide.

In the future, the large-scale integration of environmental data by computer can be expected to merge specific company and national data, satellite data, and data collected real-time by large numbers of ground-based electronic and biological sensors, to provide a truly global real-time picture of environmental conditions. Sensors already being used around the world for continuous, unattended environmental monitoring include solid-state devices that use ultrasound to measure wind speed and direction, and temperature; and infrared photo-acoustic atmospheric gas sampling devices that can continuously and selectively monitor for parts-per-billion traces of toxic or pollutant gas in the atmosphere. “Biochip” sensors based on active biological sensing components are also being introduced.

Obtaining and displaying 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. Much, however, depends on our theoretical understanding of natural ecology. Ecology is not by any means a mature science, and simply does not yet have an adequate large-scale understanding of aggregate ecological processes. In the period 1980 to 1987, 50 percent of all ecological studies were conducted on areas less than one meter in diameter, and 25 percent dealt with areas less than 25 centimeters in diameter. Similarly, a survey of literature in 1989 showed that 40 percent of ecological experiments lasted for less



*Information technology can be used to integrate environmental, technical, and management data.*

If industry is to enjoy rational environmental policy, it has a clear interest in the development of good ecological theory.

than a year, and that only seven percent lasted five or more years.<sup>11</sup> A report published in 1990 by the Ecological Society of America (ESA), *Sustainable Biosphere Initiative: An Ecological Research Agenda*,<sup>12</sup> emphasizes the need for a wider perspective, and proposes a list of ten research priorities for ecological research in response to global environmental problems. It also identifies twelve “intellectual frontiers of ecology” that focus on issues of primary importance for management of the interface between industry and the ecosystem.

In ecology today, fundamental aspects of understanding are in ferment. The application of “chaos theory,” the principles of sociobiology, and even the Gaia theory, are challenging an earlier picture of the stability and evolution of ecosystems. A view is emerging that sees ecosystems as “self-organizing” systems, in which order and complexity are “emergent” properties, not accidents. As living communities they are able to maintain themselves independently of the precise mix of species that compose them, as these can be in constant flux while the ecosystem itself is sustained.

If ecosystems are “chaotic” systems, they may have the ability to appear robust and resilient until changing overall system inputs reach a level at which there is a sudden “jump” to a qualitatively different pattern of self-organization. Such changing inputs may well include increases in the amount of energy being released in the system, or changes in the identity and amounts of chemicals flowing in the system. And the “inert” or abiotic part of the natural environment may similarly not be just the coincidental frame in which life finds itself, but be the result of active collective regulation by all living organisms. The “strong” version of this view is the Gaia theory, which sees the entire planet as a single living organism.<sup>13</sup> In support of this view, it can be shown that the gas composition of the atmosphere is not chemically stable, and is being maintained only by the activities of living organisms, and that much crustal rock can be considered to be the product of living processes, much as is the inert shell of a lobster.

Whatever the final form of these ideas, their resolution holds considerable practical significance for environmental management by industry. 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 deliberately introduced 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?

On the last point, prevailing policies stressing pollution control were based on the idea that the environment had an unlimited capacity to assimilate small amounts of pollutants without harm, but findings that this is not true are now leading to a shift in policy to emphasize pollution prevention. Ten states have already passed toxics use reduction laws modeled on this thinking, but does this mean, by extension, that all individual industrial processes in the future should be closed systems? 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 example, a net industrial producer of carbon dioxide (CO<sub>2</sub>) at one location might be

balanced by a net industrial absorber of CO<sub>2</sub> at another location, with the atmosphere acting as the link or transfer medium. This kind of transfer is actually already happening—as the Italian agrochemicals group Ferruzzi has shown by its calculation that it is a net absorber of CO<sub>2</sub>.<sup>14</sup> Finding good answers to questions such as these will have considerable practical significance for industry in the years ahead, and can be expected to be an important aspect of industrial ecology.

Industrial ecology will also be concerned with maintaining rates of natural resource use at sustainable levels and with tolerable environmental impacts. In the case of activities such as mining, the ecological significance of surface rock formations will need to be considered, as with recently emerging concern about the mining of limestone in England, which results in the loss not only of unique habitats and scenery, but also of a very significant water reservoir. The limestone region of the Mendip hills in southern England, for example, which has lost 190 million tons of hard limestone to quarrying in the last 20 years, supplies 90 billion litres of drinking water a year, 40 percent more water per unit area than any other aquifer in southern England.<sup>15</sup> The concept of “renewable mining”—the substitution of, say, volcanic basalt for many mundane uses of sedimentary rock—may yet take hold. However, the mere selection of renewable resources is not enough to avoid significant modification of ecosystems. The planting of “factory forests,” for example, where old growth forests once stood, can lead to a dramatic reduction in species diversity.<sup>16</sup> Clearly, more is needed than the convenience of a single species monoculture if entire ecosystems are to be sustainably exploited on an industrial scale.

In support of practical application of ecological understanding, it may prove possible to develop specific indicators or indexes that quantify the impact of industrial ecosystems on aspects of the natural environment. For instance, an industrial facility could be given a score for its net CO<sub>2</sub> balance with the environment, and this score could be used to facilitate industry comparisons, the quantification of environmental audits, or provide a basis for the assessment of a carbon tax. The severity of impact on natural ecosystems might also be assessed by the timescale over which recovery will occur. This depends on which of three recovery mechanisms are called into play. The first, and most rapid, is population regrowth, which occurs when a single species is affected. The second is “succession,” in which many species are affected, and in which recovery involves recreation of the entire ecosystem as food chains are rebuilt from the bottom up, a process that can take considerably longer. The third recovery mechanism, with the longest timescale, is evolution, required in cases where human change to the environment is so extreme that recolonization actually requires new organisms.

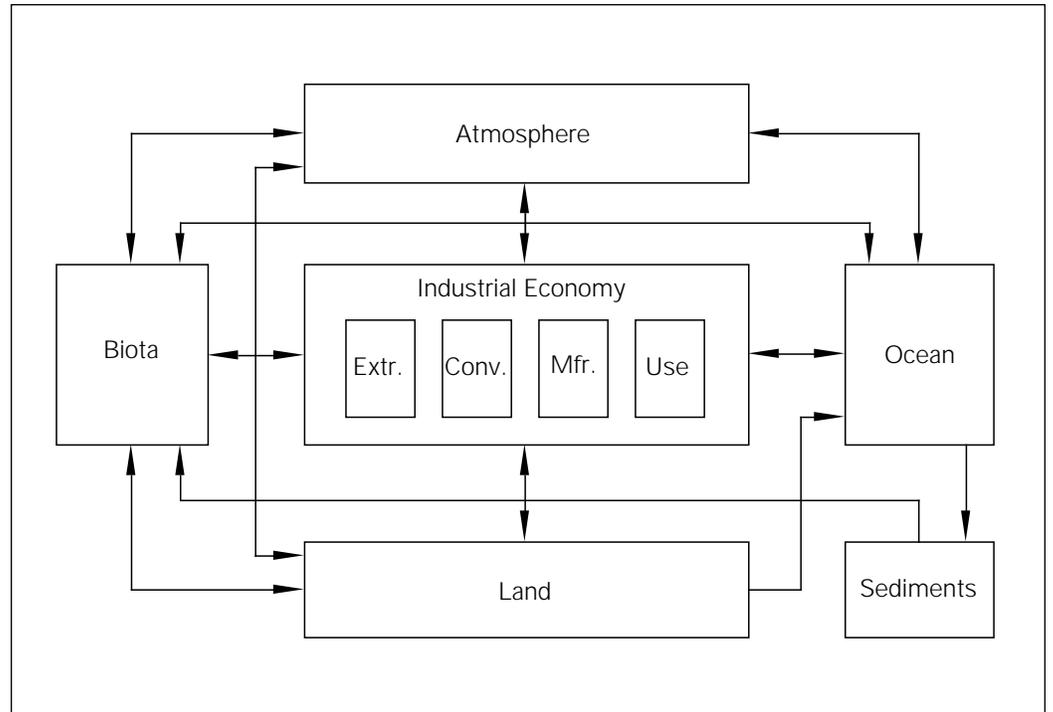
The flows of chemicals between industry and the biosphere can be mapped using the “mass balance” approach and the concept of “materials cycles.” The “mass balance” method uses numerical data for direct inputs of materials, available from economic statistics or individual company records, in combination with chemical or engineering details of the processes being studied. This can give more accurate assessment of waste releases into the environment than direct measurement of waste streams, particularly when the wastes are emitted along with large volumes of combustion products or wastewater.

The concept of “materials cycles” is an extension of the idea of biological cycles, such as the carbon and nitrogen cycles, to include flows within the industrial system. Quantified flow charts of the type shown generically in Figure 5 can be used to integrate a



*Specific indicators or indexes could quantify the impact of industrial ecosystems on aspects of the natural environment.*

**Figure 5:**  
Basic flow diagram for  
the interface between  
industry and the  
environment



wide array of data, providing a basis for comparing natural and industrial flows, in terms of volumes, flow paths, and environmental sinks. They are an excellent starting point for analysis of the environmental impact of industrial flows, and for the development of environmental improvements and modifications by exploiting potential trade-offs and choices. They can also serve as communications tools for conveying the logic and rationale of complex environmental decisions in an accessible way.

*“Dematerialization” is an established trend in industrialized economies, and is being driven by four factors.*

Ultimately, with sufficiently subtle understanding and genuine concern, active management of the industrial interface with the biosphere may become a coordinated effort of environmental monitoring and real-time adjustment comparable to the management of large infrastructure networks—such as demand and supply management in electricity grids, or traffic routing management in national telephone systems.

### **3 • Dematerialization of industrial output**

Much of the environmental impact of industrial activity is a result of the energy consumption and mobilization of matter that make industrial production possible. In the environmental debate beginning in the 1970s it was assumed that increases in economic prosperity and further economic growth were inevitably linked with worsened environmental impact. It was therefore argued that economic growth and industrial activity would have to be slowed or reversed in order to solve environmental problems in any fundamental way. Today, this relationship is no longer obvious.

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 levelled off when measured in terms of the quantity consumed per capita. 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.<sup>17</sup> And micro-structural engineering of smart materials is yielding ever lighter, higher-performance components.

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

- First, the cost of producing materials has been increasing, largely because materials processing tends to be energy-intensive.
- Second, 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, since each kilogram of high-strength steel replaces 1.3 kilograms of standard carbon steel.<sup>18</sup>
- Third, 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 essentially saturated, and consists primarily of replacement demand.
- Fourth, following on the last point, discretionary income now tends to be spent on goods and services with a lower materials content per consumer dollar, since there are no major new consumer product categories with a high materials content per dollar.

The basic trend to dematerialization appears well established, and is clearly environmentally favorable, since 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. Nevertheless, there are a number of factors that run counter to dematerialization, and with which industrial ecology needs to be concerned. The first is product quality. Improvements in product quality generally lead to enhanced dematerialization, but if product quality is poor, although individual product mass may be lower, products are likely to be discarded sooner, leading to increased materialization of waste. Linked with this 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. In many cases products are no longer assembled with traditional fasteners such as screws and cannot be dismantled without destroying their components. In addition, components frequently represent a mix of different materials and cannot easily be recycled. Recent legislation in Germany mandating the ability to dismantle cars rapidly into homogenous component parts, is likely to lead to widespread development of DFD skills.

At the same time, there needs to be a recognition that although improvements in technology and materials science tend to lead to long-term gains in dematerialization, there may need to be tolerance for transient increases in materialization while a new technology is establishing itself. A case in point would be the major growth in demand for office paper caused by information technology—desktop computers and photocopiers. In spite of the fact that the microchip is perhaps the best example of technology with a dramatically declining ratio of product mass to dollar value, and product mass to embedded knowledge, the “paperless office” has failed to arrive. Yet the accelerated



*New materials give improved performance with less mass than the basic materials they replace.*

*The energy and mass consumed in manufacturing per dollar of product value may come to be an important attribute of new products.*

materialization of paper could be reversed by perhaps three further innovations, each of which the computer industry is striving to develop: an increase in the image resolution of computer displays to just beyond the limit of optical resolution of the human eye (the strategy used in good four-color process printing, but not yet reached even by high-definition television), combined with readily portable large-area displays (transistorized “active matrix” flat panel displays are moving well in this direction), and a really convincing permanent memory medium (magneto-optical disks and drives are a good potential candidate since they are impervious to stray magnetic fields). Together, these could make reading from a computer as acceptable as reading from a piece of paper, and could remove the feeling that paper was needed for secure storage.

Industrial ecology could introduce “materialization impact statements” or an “index of materialization” for products and technologies to focus the need for additional development effort specifically aimed at enhancing dematerialization. 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. Thus, materialization impact assessments could 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 kWh/\$, or kg/\$, as an important attribute of new products we are planning to buy.

An example of a conscious move to energy “dematerialization” is being provided by the recent move by many electricity generating utilities to deal with growing electricity demand in a new way. Utilities in 19 states have chosen to invest in energy conservation as an alternative to new generating capacity. By offering users energy saving technology, such as compact fluorescent lamps, and adding a fractional charge to their bills over an extended period, they can continue to show a good return on investment while at the same time meeting demand, and without incurring the environmental impact of increased electricity generating capacity. This demonstrates that with enough ingenuity, profitable operation of a business can be deliberately and successfully decoupled from growth in materialization.

Lastly, industrial ecology would not only seek the deliberate enhancement and acceleration of dematerialization, but also look for ways for newly industrializing economies to leapfrog over older, highly materializing industrial practices to develop intrinsically less environmentally demanding industrial patterns from the outset. By focusing advanced materials and design knowledge on the opportunities for radical dematerialization of basic civil infrastructure, it may prove possible to sidestep the massive materials use that has until now been seen as an intrinsic feature of the early stages of industrialization.

The available evidence suggests that it is possible to think in terms of increasing the efficiency of industrialization as an aggregate activity, since as national economies have successively industrialized, their respective peak energy intensities have fallen steadily. When the UK industrialized it was using the equivalent of about 1.02 metric tons of petroleum to yield \$1000 of Gross Domestic Product (GDP) at its peak intensity in 1880. When US energy intensity peaked in 1915 it was at the equivalent of about 0.95 tons, whereas Japan, one of the more recent countries to industrialize, peaked at only about 0.42 tons in 1950.<sup>19</sup> The average energy intensity of industrialized economies today is about 0.35 tons, but the peak value for economies that are currently industrializing is somewhat higher.

A deliberate effort to develop technologies for dematerialization could provide businesses in industrially developed countries with excellent new markets while at the same time making a crucial contribution to global environmental quality.

#### **4 • Improving the metabolic pathways of industrial processes and materials use**

Industrial ecosystems and industrial metabolism are parallel concepts. The idea of the industrial ecosystem focuses on the efficient interchange of byproducts and intermediates between industrial players, which roughly correspond to the individuals of a species in the biological ecosystem. Industrial metabolism,<sup>20</sup> on the other hand, is concerned with the efficiency of the metabolic processes occurring within the individuals of the species, which roughly correspond to the individual firms or industrial process operations. In biology, metabolism refers to the chemical processes and pathways within the living organism by which food is assimilated, complex chemicals are synthesized for maintenance and growth, and energy is stored or released.

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. Reducing the number of process steps can be a powerful means to increased energy efficiency. If a complete process has four steps, each with 60 percent energy conversion efficiency, the efficiency of the total process is the arithmetical product of the steps: 12 percent. If the process had only three steps, its efficiency would be 21 percent. Deleting process steps is often more feasible than achieving the equivalent incremental improvements in the efficiency of each step.

In addition, many of the end uses of materials are dissipative—that is, they are dispersed into the environment as they are used, with no hope of recovery for recycling.<sup>21</sup> Car and truck brake pads and tires, for example, leave a finely distributed powder on our highways as they wear down. This dispersion becomes more serious when toxic heavy metals are involved. Changes in technology could avoid dissipative uses of materials—in the case of car brakes, for example, vehicles could in principle use electrically-regenerative or flywheel-storage braking that not only avoids thermally- and materially-dissipative friction, but actually recaptures the vehicle's energy of motion and stores it for later use.

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, while regenerating process intermediates much as the energy carrier adenosine triphosphate (ATP) is regenerated in cellular metabolism. Biological metabolism is primarily fueled by solar energy and operates at ambient temperatures and pressures: if this were true of industrial metabolism, there could be significant gains in plant operating safety. 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 further.<sup>22</sup>



*Study of the type and pattern of chemical reactions and materials flows in the industrial system indicates potential areas of improvement.*

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. Initiated in 1975, the 3P Program has resulted in more than 2,700 successful projects in its first 15 years, while yielding \$500 million in savings for the company and a 50 percent reduction in pollution per unit of production.

*3M's “3P” program is an example of the industrial metabolic improvement approach in practice.*

Many of 3M's products involve coating processes. Typically, coatings are dissolved in solvents, so that they can be applied evenly and thinly; the solvents are then dried off with heat. The problem is that, as they dry, solvents like toluene, xylene, and methyl ethyl ketone are released into the air. Pollution control equipment can reduce these air emissions by as much as 85 percent, but these “add-ons” are expensive to operate and still allow 10 to 15 percent of the solvents to be released. 3P was an attempt to find lower cost and longer-lasting solutions. Its objective was simple: to prevent pollution at the source in both products and manufacturing processes, rather than removing it from effluent after it has been created.

Although the concept was not unique, even at the time it was instituted, the idea of applying pollution prevention companywide and worldwide, and recording the results, had not been attempted before 3M's initiative. 3P encourages technical innovation to prevent pollution at the source through four methods: product reformulation, process modification, equipment redesign, and resource recovery. Projects that use one of these methods to eliminate or reduce pollution, save resources and money, and advance technology or engineering practice are eligible for recognition under 3P. In the course of 15 years, worldwide annual releases of air, water, sludge, and municipal solid waste pollutants from 3M operations has been reduced by half a million tons, with about 95 percent of the reductions coming from U.S. operations.<sup>23</sup>

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. The creation of industrial ecosystems would be made easier, as would management of the interface between industry and the biosphere. 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 modest, systematic process improvements, industrial metabolism has much to offer as a way of thinking about the environmental compatibility of industrial processes, and for this reason is an important component of industrial ecology.

### **5 • 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 they are based on finite fossil energy resources. Even nuclear fission, viewed over the long term, probably suffers from a low or even negative net energy yield when the total “life cycle” cost of construction, fuel production, decontamination, decommissioning, and waste storage is deducted. 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<sub>2</sub> 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<sub>2</sub>. But the amount of carbon in fossil fuel varies significantly. Expressed as the proportion of carbon to hydrogen, fuelwood is roughly 91 percent carbon, coal 50 percent, oil 33 percent, and natural gas only 20 percent carbon.<sup>24</sup> 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.<sup>25</sup>

This attractive characteristic has led to the concept of a future “hydrogen economy.” Although formidable practical development hurdles need to be overcome, 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 (energy for hydrogen production can also be supplied by fossil fuels or nuclear power, but the total system would then no longer be based on ambient energy). 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. A study conducted in 1989 at the Center for Energy and Environmental Studies at Princeton University compared the flammability, energy of ignition, and speed of travel through air, of hydrogen, natural gas and gasoline, and found that no fuel was inherently safer than the others.<sup>26</sup> The logistics and business infrastructure of a hydrogen supply industry would appear to resemble those of the existing oil industry, and as a result the scenario is of interest to major oil companies. In Germany, the Federal Ministry of Research and Technology is funding research by Mercedes-Benz into hydrogen-fueled vehicles. In Canada, there are plans to construct a hydroelectric-powered 100-megawatt pilot plant capable of producing 2 tons of hydrogen an hour. The hydrogen would be shipped to Europe under an agreement with the European Commission.

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 scenario may not represent the final shape of the energy supply infrastructure of the future, but it does illustrate the systemic thinking that is required. Already, aspects of this logic are being applied. Construction of new electricity generating capacity around the world is tending to favor highly efficient combined-cycle gas turbine technology that burns natural gas, and natural gas is widely seen as the low-carbon “bridge” to a post-fossil fuel economy. Industrial ecology will be intensely concerned to promote the development of an energy supply system that functions as a part of the industrial ecosystem, and is free of the negative environmental impacts associated with current patterns of energy use.



*The fuels used as the industrial system has evolved have become increasingly hydrogen-rich and carbon-free.*

## **6 • Policy alignment with a long-term perspective of industrial system evolution**

As industrial ecology frames a new paradigm for structural balance and environmental optimization in the industrial system, it cannot avoid the inevitable policy dimension of such a broad goal. If it is to achieve its full impact, it will certainly need to be backed up by innovative new policies that coherently align financial, economic, and regulatory score-keeping on an international basis. There are a variety of policy issues that need to be addressed in order to do this.

Probably the primary policy concern is the need to reflect the true costs of environmental degradation in market pricing.

Probably the primary policy concern is the resolution of the extensive debate in recent years about the need to reflect the true costs of environmental degradation in market pricing. The tax on CFCs following the Montreal Protocol is clear evidence that even in the United States there is a basic willingness to redirect technology for environmental ends. The real question now is what form the full range of these attributed costs will take, when and how they will be applied, and with what degree of consistency across jurisdictions.

It appears inevitable that steps will be taken internationally to place a money price on environmental damage—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” or “Pigovian” taxes (after the economist Pigou), such as the tax on CFCs. Proposals have been made for a tax of anywhere from \$6 to \$28 per ton on carbon-containing fuels to counter the release of carbon dioxide, and it has been suggested that similar taxes could be applied to environmental issues ranging from the use of virgin rather than recycled materials, to the overpumping of groundwater. Most such proposals recommend that there should be an offsetting reduction in personal and corporate income taxes, or that the revenue stream should be used to fund a transition to an ecologically benign economy.

An alternative approach to the transfer of environmental costs is being proposed by those who say green taxes would simply generate additional bureaucratic inertia. They propose instead that governments should 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 over time, the government could issue—or auction—a progressively smaller pool of permits each year, or buy them back from a permanent pool to remove them from the market, as could others, for example environmental groups. The United States Environmental Protection Agency (EPA) 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 this program appear to be working within its defined limits, but in 1988 3M voluntarily returned rather than sold 150 tons of air emission credits worth more than \$1 million in order to ensure that its efforts resulted in a net reduction of air pollution.

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 two or three 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 rates of growth or ecosystem recovery rates.<sup>27</sup>

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” (IESW), which accounts for a variety of environmental deficits.<sup>28</sup>

On a somewhat different tack, research with historical data indicates that the industrial system as a whole shows evidence of “regularities,” predictably structured patterns of evolution and growth.<sup>29</sup> These regularities essentially show that such things as the emergence of new technologies, or the progressive sophistication of fuel sources, have growth patterns that follow consistent and predictable S-shaped curves. An awareness of these patterns can have value in ensuring that policy is not swimming upstream against emergent characteristics of the industrial system.

Environmental legislation needs to be both robust, and flexible and experimental in spirit, with a provision for self-correction: attributes that are often difficult to achieve in practice. Sometimes there may be potential for non-legislative means of policy implementation. An example is the EPA’s “Green Lights” program. This involves voluntary “contracts” between the EPA and individual companies that commit them to install advanced, cost-saving lighting fixtures and lamps. The EPA supplies technical and cost information, and, crucially, the motivation for an energy-saving measure which might otherwise not occur simply because it was too low a priority on the corporate agenda.

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

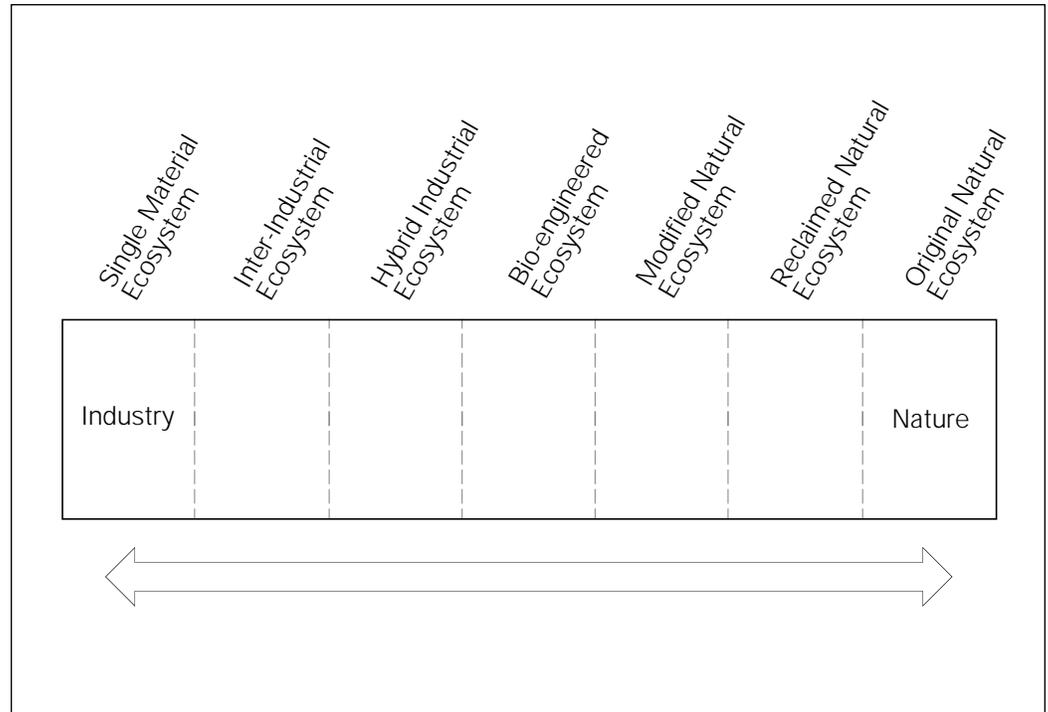
Looking ahead, the long run outcome of an industrial ecology approach can be sketched in outline. In terms of the types of ecosystems that will exist, it is likely that there will be not just one class of industrial ecosystem, but an entire spectrum of ecosystems. These would run from single material 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 (see Figure 6). 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. This is not unprecedented—the “green and pleasant land” of 19th and early 20th century England was almost entirely shaped by human activity, as



*Human modification and manipulation of ecosystems is as old as agriculture. The challenge now is to integrate industry.*

**Figure 6:**  
The likely future  
spectrum of ecosystem  
types



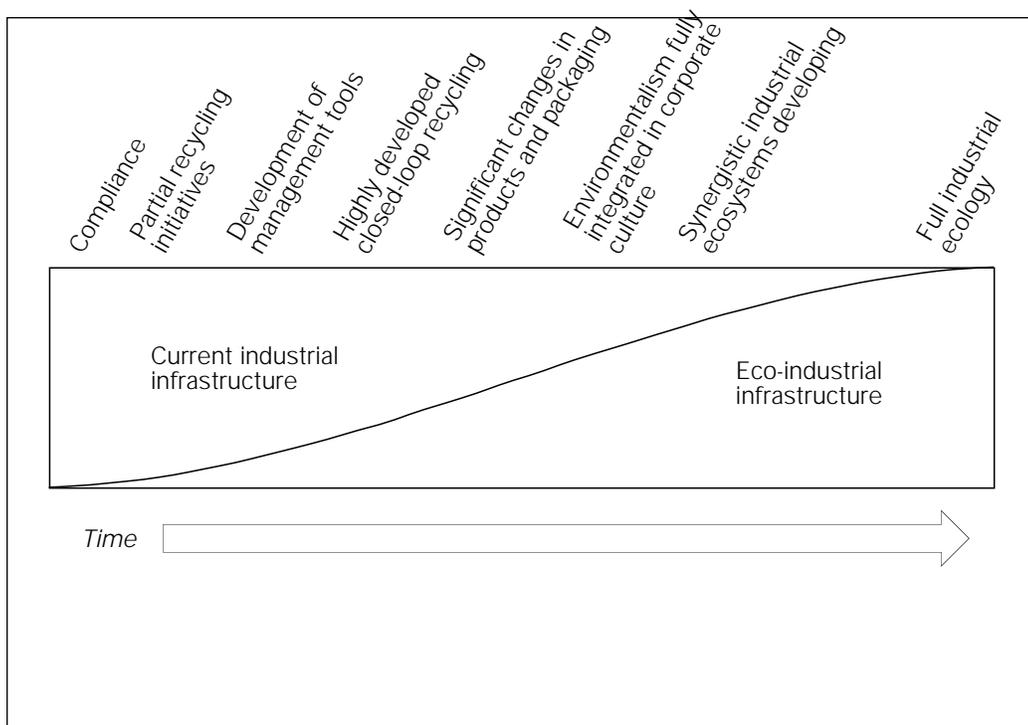
are the ubiquitous, and exquisitely productive, sculpted rice paddies on the mountain slopes of Java and Bali. The “gardening of the planet” need not be as far-fetched as it sounds.

*The ability to define natural systems in process terms will be essential to monitoring and regulating our impact on the environment.*

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

A “vision of the environment,” or a “target state” for the natural world, will need in part to be expressed in terms of dynamic processes, not only in terms of static ecosystem elements—a mere listing of species. Our picture of an ecosystem tends to be focused on the actors—but it is their actions and the contribution they make that are important to the maintenance of the ecosystem. Ecosystems tend to be in continual flux, with the mix of species changing over time, and we will need to recognize this by identifying the values and outputs that are contributed by these dynamic elements.

Another dimension of environmental quality is the recreational and aesthetic value of the natural environment. It is clear that scientific and technical arguments are not the sole driving factor in public concern about environmental issues. People derive high emotional and psychic value from the health and beauty of their environment, and corporations might wonder if they should establish a parallel between this and the care they devote to high aesthetic quality in marketing. One aspect of a company’s image may come to be the contribution it makes to shaping its customer’s total quality of life—not merely in the products it supplies, but also in ensuring that it does not in the process degrade other aspects of that person’s life experience. An example of this would



**Figure 7:**  
The emergence of an  
eco-industrial  
infrastructure

be the brilliant advertisement run by Shell in the United Kingdom a decade ago, showing a shimmering vista of English countryside alongside this headline: “Wouldn’t you protest if Shell ran a pipeline through this beautiful countryside?” followed on the next line by “They already have!”<sup>30</sup> In this very effective advertisement, the appeal was grounded in the company’s concern and competence in terms of the pure aesthetic quality of the environment.

The definition of nature and of environmental quality will not, in short, be something we can take for granted, but something we will have to make a positive effort to formulate. This will be a cultural challenge, as well as a challenge of knowledge and analysis for ecology, but it will be vital to creating an optimal interface between industry and the biosphere. The task of industrial ecology will be to provide the means of maintaining the key defined parameters of the natural environment, allowing the industrial players to collectively “condition” their environment in a manner reminiscent of the Gaia theory.

The result of an industrial ecological approach over time will be a gradual overall transition, taking several decades, to an eco-industrial infrastructure (see Figure 7), so that all process systems and equipment, and plant and factory design, will eventually be built 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.

*A dominant new generation of technology will be characterized by its ability to interlock with other parts of an industrial ecosystem.*

## 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.

Executives and policymakers who absorb and appreciate this new mode of thinking now will be at a very real advantage in the world of the future.

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.<sup>31</sup> 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.

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