Industrial Ecology at the Crossroads

Feature

By Thomas E. Graedel

Industrial ecology, an emerging field less than a decade old, faces an important predicament. In its initial implementation, best characterized as pollution prevention, it has made substantial strides in reducing the negative impact of our technological society on the environment. Further improvement, however, can no longer be accomplished by small incremental gains; it will require new concepts, new materials, and new processes. Physicists can make major contributions to all three.

The science of sustainability needs new concepts, materials, and processes

Sometimes termed the science and technology of sustainability, industrial ecology focuses on societal and technological development that is sustainable over the long term. It is not merely some feel-good movement, but a vital necessity in this time of concern about pollution hazards and finite natural resources. Indeed, it serves as the paradigm around which much industrial design and development activity centers. In this context, the word ecology implies that one should conserve and reuse resources of all kinds, as is characteristic of biological systems.

The industrial process can be conveniently pictured as having four central elements: the materials extractor or grower, the materials processor or manufacturer, the user, and the scavenger. To the extent that each encourages recycling of materials within the entire industrial system, the industrial process evolves into more efficient modes of operation that have less disruptive impact on the environment and that more resemble the behavior of biological ecosystems.

Industrial ecology remains merely a fuzzy concept unless informed decisions by conscientious technologists and managers embed it into industrial activities. This is accomplished by actions that encourage the flow of materials and energy in the industrial ecology system (Figure 1). Among these desirable actions are to design materials and products that do more with less, to increase the recoverability of materials rather than their dissipation into the environment, and to encourage the upgrading rather than the discarding of products through obsolescence.

Enabling industrial ecology

Like biological ecology, industrial ecology evolves as a consequence of millions of tiny acts (e.g., a more efficient way to assemble and disassemble a fixture, an innovative component made from only a single material, an industrial process changed to avoid generating a toxic by-product). The materials, components, and technologies that are available inevitably will limit the accomplishments of industrial product and process designers, unless new ones are designed.

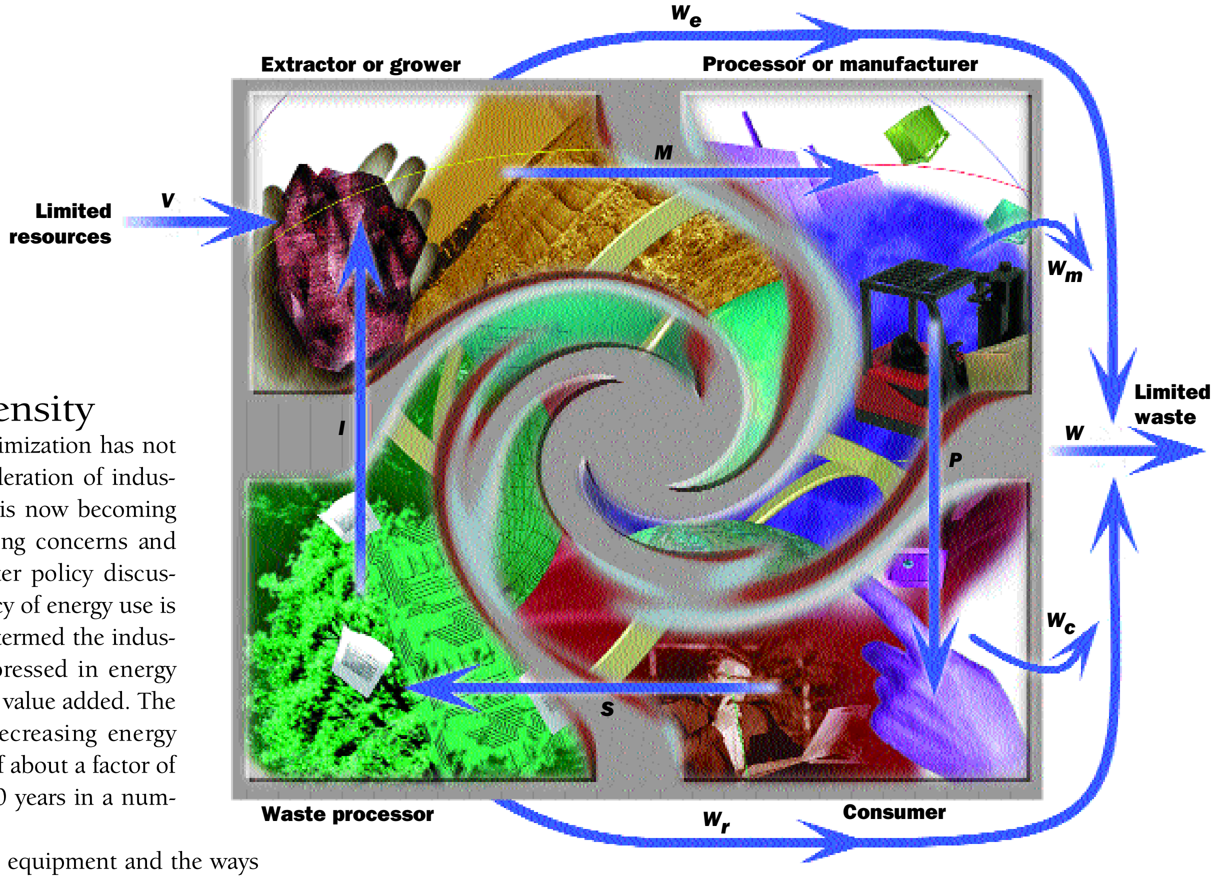
Today's materials are characterized by attractive properties such as robust structural performance, rapid device function, and efficiency of manufacture. However, many of these same materials possess environmentally undesirable features such as requiring high-energy inputs, containing difficult-to-separate constituents, or containing biologically harmful chemicals.

Historically, physicists and materials scientists have not regarded environmental factors as important aspects of their work. The next generation of materials and processes can only achieve global sustainability if physicists change their attitudes, become practicing industrial ecologists, and incorporate that perspective into their work.

Dematerialization

In the process known as dematerialization, lesser amounts of materials are used to make products that perform the same functions as their predecessors. The ultimate example is the integrated circuit, where the packing density has increased exponentially since 1960. The most recent efforts in electronic dematerialization have used light beams or tiny microscope tips to move single atoms from place to place on a surface. Such work may eventually lead to circuits with electrical constituents only a few atoms in size that work at much greater speeds and require much less power.

Electronic circuits are not the only components getting smaller. Various microfabrication techniques are yielding flow sensors, gear trains, and micromotors measuring less than 100 μm in diameter. As development continues and components such as microvalves and micropumps are produced, "nanoengineers" envision entire microsystems incorporating electrical, mechanical, thermal, optical, magnetic, and chemical functions operating on a single small silicon chip—even a whole chemical laboratory on a chip. Potential uses include micromotors for security and medical applications and microrobots for assembly tasks at submillimeter scales.



Less energy intensity

In the past, energy minimization has not ranked as a central consideration of industrial process designers. It is now becoming more so, as global warming concerns and energy taxes begin to enter policy discussions. The relative efficiency of energy use is measured by a parameter termed the industrial energy intensity, expressed in energy units per monetary unit of value added. The recent trend is toward decreasing energy intensity, with decreases of about a factor of 3 occuring over the last 30 years in a number of countries.

The design of industrial equipment and the ways in which industry extracts and processes resources play major roles in the rate of energy use. This, in turn, affects the rate at which humans generate carbon dioxide and other potential global climate-change gases. Devices that reduce power consumption, processes that operate more efficiently, and resource provisioning that minimizes energy consumption are all important in continuing to change the historical pattern.

Mining residues

One intriguing discovery of industrial ecology is that many resource extraction efforts may today focus on the wrong supply. David Allen of the University of Texas has plotted the dilution of metals in industrial residue streams against the current cost of those resources and compared the result with that for virgin materials. His surprising analysis indicates that for a number of metals it would be more productive to get resources from industrial residues rather than from mines in the planet's crust because the resources exist in higher concentrations in the industrial residues than in presently accessible ore bodies.

If residue streams are richer than the ores, why are we not vigorously mining them? The reasons are partly technological, partly political. On the technological front, little research and development effort has gone into utilizing modern technology in recycling. Technologists must willingly regard the development of innovative residue-recovery techniques as of more technological interest and importance than the mining of virgin resources. They need to pay more attention to efficient separation of materials and to ways of avoiding mingling them in the first place, through all stages of production.

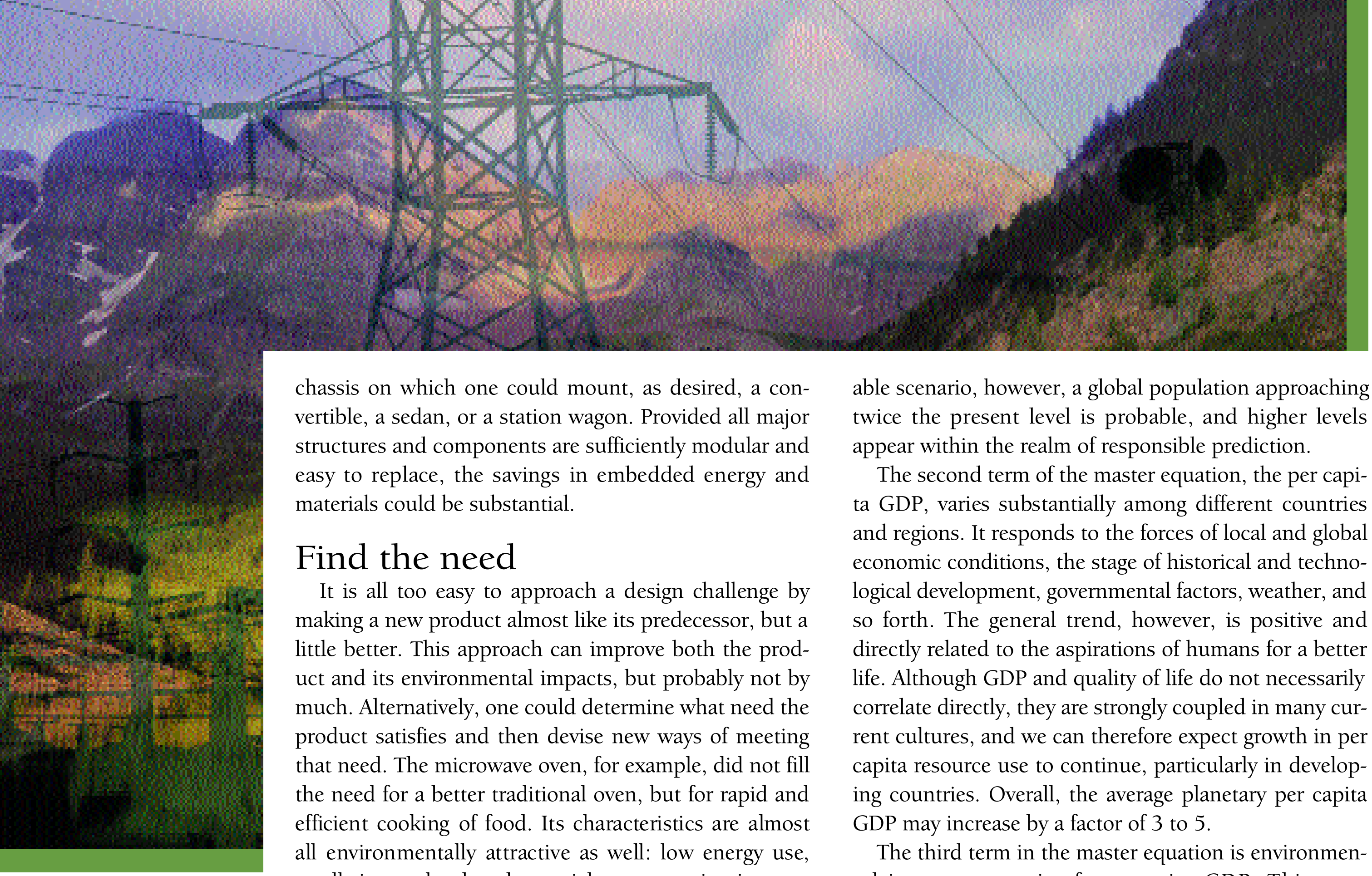
On the political side, a number of practices—energy subsidies, entrenched infrastructure, and international trade agreements—favor the extraction of virgin materials. For at least some materials and in at least some regions of the world, virgin resources are strongly limited, yet residue streams are abundant and ripe for recovery. A good example is the failure by many small plants and laboratories to recover silver after photographic processing, which accounts for about half of all silver used today. Technological priorities in research and development need redirection toward a "reuse" perspective.

Upgrade, don't discard

Industrial products of earlier times were characterized by modularity. They were expected to last a long time and designed so that components that might wear out were fairly easily replaced. Today's products often reveal a different approach: once a defect occurs, the expense of repair or part replacement is prohibitive, so the product is discarded. For a number of products, repair is impossible no matter what the expense. As a result, products containing materials won from Earth's crust with great expenditures of energy and significant associated environmental impacts get discarded without a thought of the valuable resources embedded within.

Some companies are reverting to the earlier approach and stressing modularity. For instance, a Siemen Nixdorf laptop computer is advertised as fully modular. It has a replaceable keyboard, interchangeable screens, and alternative disc drives. A Mercedes-Benz concept, not yet fully realized, envisions a long-life automobile

Figure 1. A model of the industrial metabolic system: V, virgin materials; M, processed materials; P, products; S, salvaged materials; I impure materials; W, waste; e, extractor; m, manufacturer; c, consumer; r, recycle.



chassis on which one could mount, as desired, a convertible, a sedan, or a station wagon. Provided all major structures and components are sufficiently modular and easy to replace, the savings in embedded energy and materials could be substantial.

Find the need

It is all too easy to approach a design challenge by making a new product almost like its predecessor, but a little better. This approach can improve both the product and its environmental impacts, but probably not by much. Alternatively, one could determine what need the product satisfies and then devise new ways of meeting that need. The microwave oven, for example, did not fill the need for a better traditional oven, but for rapid and efficient cooking of food. Its characteristics are almost all environmentally attractive as well: low energy use, small size, and reduced materials consumption in manufacture. The archetypal example is, of course, the transistor, which filled the need for rapid, energy-efficient switching of electrical currents. Again, its attributes were environmentally beneficial.

To identify needs and to invent new ways of meeting them, industrial physicists will need to spend time with engineering design teams, perhaps even marketing staffs. The most successful industrial physicists turned industrial ecologists will be those who know how needs are currently being met, what isn't working as well as it might, and how new ideas might prove beneficial.

Transition to sustainability

A useful way to think about the most effective response society can make to environmental stresses is to examine the predominant factors involved in generating those stresses. Obviously, many of the stresses are strongly influenced by the needs of a population and by the standard of living it desires. An expression of these driving forces is provided by the "master equation":

> Environmental impact = population × GDP per person × environmental impact per unit of per capita GDP

where GDP is a country's gross domestic product, a measure of industrial and economic activity. Let us examine the three terms on the right side of this equation and their probable change with time.

Earth's population is, of course, increasing rapidly. The time and apex of Earth's eventual human population peak remain uncertain. Even in the mildest reasonable scenario, however, a global population approaching twice the present level is probable, and higher levels appear within the realm of responsible prediction.

The second term of the master equation, the per capita GDP, varies substantially among different countries and regions. It responds to the forces of local and global economic conditions, the stage of historical and technological development, governmental factors, weather, and so forth. The general trend, however, is positive and directly related to the aspirations of humans for a better life. Although GDP and quality of life do not necessarily correlate directly, they are strongly coupled in many current cultures, and we can therefore expect growth in per capita resource use to continue, particularly in developing countries. Overall, the average planetary per capita GDP may increase by a factor of 3 to 5.

The third term in the master equation is environmental impact per unit of per capita GDP. This term expresses the degree to which technology is available to permit development without serious environmental consequences, and how extensively that technology is deployed. Although this third term is primarily a technological term, societal and economic issues provide strong constraints to changing it rapidly and dramatically. For example, a major shift to public transportation would have enormous implications for energy conservation and pollution control, but this also would require a major change in the public's desire to drive to work in private vehicles.

The best chance of mitigating the environmental impact of technology lies with this third term, which thus offers the greatest hope for a transition to sustainable development. Modifying this term is a central tenet of industrial ecology. Given the anticipated increases in population and average GDP, and the sense that we are already having too great an impact on the planet's natural systems, we must decrease the third term by a factor of at least 10, and more probably by 20 to 50. This "sustainability factor" will be difficult to reach, and it clearly demands innovative step-function change, not incremental change.

BIOGRAPHY

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