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19 INDUSTRIAL ECOLOGY AND ENVIRONMENTAL CHEMISTRY

19.1 INTRODUCTION AND HISTORY

At the beginning of Chapter 11, mention was made of the **anthrosphere** consisting of the things humans construct, use, and do in the environment. The anthrosphere constitutes a fifth sphere of the environment, along with the geosphere, hydrosphere, atmosphere, and biosphere. Any intelligent effort to maintain and enhance environmental quality must consider the anthrosphere along with these other four spheres. This chapter is devoted primarily to the anthrosphere. In so doing, it emphasizes the emerging science of industrial ecology, defined and explained below.

Industrial ecology *is an approach based upon systems engineering and ecological principles that integrates the production and consumption aspects of the design, production, use, and termination (decommissioning) of products and services in a manner that minimizes environmental impact while optimizing utilization of resources, energy, and capital*. The practice of industrial ecology represents an environmentally acceptable, sustainable means of providing goods and services. It is closely tied with environmental chemistry, and the two sciences work synergistically with each other.

Industrial ecology works within a system of industrial ecosystems, which mimic natural ecosystems. Natural ecosystems, usually driven by solar energy and photosynthesis, consist of an assembly of mutually interacting organisms and their environment, in which materials are interchanged in a largely cyclical manner. An ideal system of industrial ecology follows the flow of energy and materials through several levels, uses wastes from one part of the system as raw material for another part, and maximizes the efficiency of energy utilization. Whereas wastes, effluents, and products used to be regarded as leaving an industrial system at the point where a product or service was sold to a consumer, industrial ecology regards such materials as part of a larger system that must be considered until a complete cycle of manufacture, use, and disposal is completed.

From the discussion above and in the remainder of this book, it can be concluded that industrial ecology is all about *cyclization of materials*. This approach is summarized in a statement attributed to Kumar Patel of the University of California at Los Angles, "The goal is *cradle to reincarnation*, since if one is practicing industrial ecology correctly there is no grave." For the practice of industrial ecology to be as efficient as possible, cyclization of materials should occur at the highest possible level of material purity and stage of product development. As just one of many examples that could be cited, consider that it is much more efficient in terms of materials, energy, and monetary costs to bond a new rubber tread to a large, expensive tire used on heavy earth moving equipment than it is to try to separate the rubber from the tire and remold it into a new one.

The basis of industrial ecology is provided by the phenomenon of **industrial metabolism**, which refers to the ways in which an industrial system handles materials and energy, extracting needed materials from sources such as ores, using energy to assemble materials in desired ways, and disassembling materials and components. In this respect, an industrial ecosystem operates in a manner analogous to biological organisms, which act on biomolecules to perform anabolism (synthesis) and catabolism (degradation).

Just as occurs with biological systems, industrial enterprises can be assembled into **industrial ecosystems**. Such systems consist of a number (preferably large and diverse) of industrial enterprises acting synergistically and, for the most part, with each utilizing products and potential wastes from other members of the system. Such systems are best assembled through natural selection and, to a greater or lesser extent, such selection has occurred throughout the world. However, recognition of the existence and desirability of smoothly functioning industrial ecosystems can provide the basis for laws and regulations (or the repeal thereof) that give impetus to the establishment and efficient operation of such systems.

The term **sustainable development** has been used to describe industrial development that can be sustained without environmental damage and to the benefit of all people. Clearly, if humankind is to survive with a reasonable standard of living, something like "sustainable development" must evolve in which use of nonrenewable resources is minimized insofar as possible, and the capability to produce renewable resources (for example, by promoting soil conservation to maintain the capacity to grow biomass) is enhanced. This will require significant behavioral changes, particularly in limiting population growth and curbing humankind's appetite for increasing consumption of goods and energy.

19.2 INDUSTRIAL ECOSYSTEMS

A group of firms that practice industrial ecology through a system of industrial metabolism that is efficient in the use of both materials and resources constitute a functional **industrial ecosystem**. Such a system can be defined as a regional cluster of industrial firms and other entities linked together in a manner that enables them to utilize byproducts, materials, and energy between various enterprises in a mutually advantageous manner.

Figure 19.1 shows the main attributes of a functional industrial ecosystem, which, in the simplest sense, processes materials powered by a relatively abundant source of energy. Materials enter the system from a raw materials source and are put in a usable form by a primary materials producer. From there the materials go into manufacturing goods for consumers. Associated with various sectors of the operation are waste processors that can take byproduct materials, upgrade them, and feed them back into the system. An efficient, functional transportation system is required for the system to work well, and good communications links must exist among the various sectors. A key material in the system is water, and it is often in limited supply in highly populated arid regions of the world.

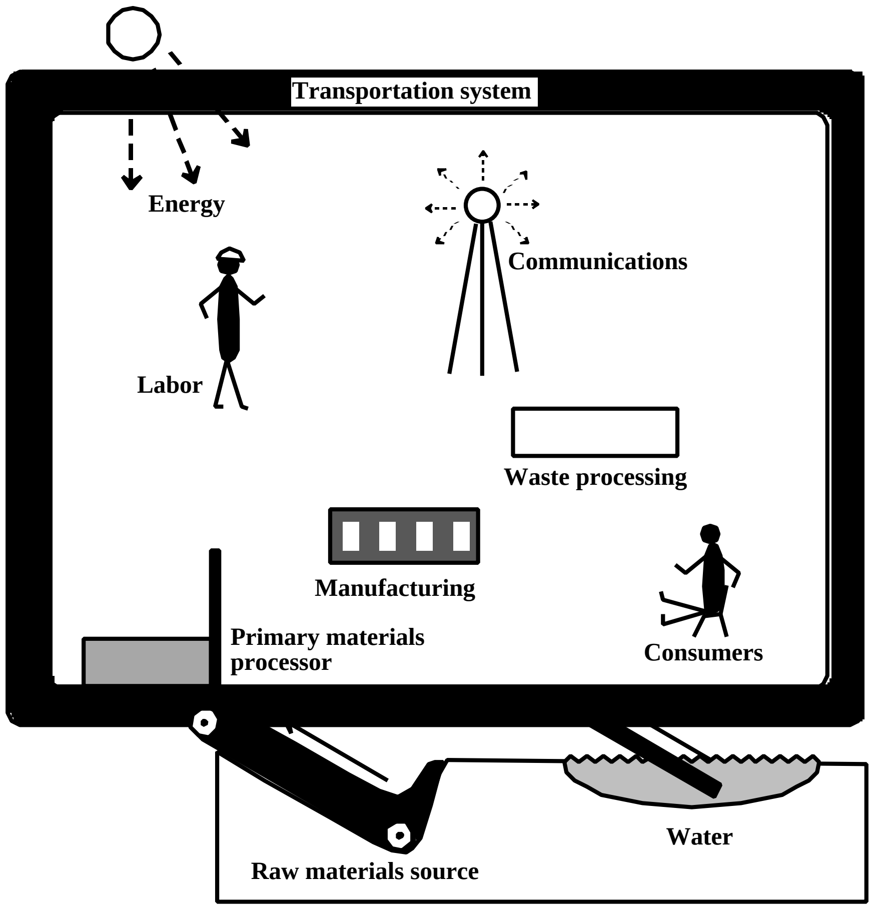

Figure 19.1 Major components required for an industrial system. When these components exist symbiotically, utilizing waste materials from one concern as feedstock for another, they compose a functioning industrial ecosystem.

A successfully operating industrial ecosystem provides several benefits. Such a system *reduces pollution*. It results in *high energy efficiency* compared to systems of firms that are not linked and it *reduces consumption of virgin materials* because it *maximizes materials recycle. Reduction of amounts of wastes* is another advantage of a functional system of industrial ecology. Finally, a key measure of the success of a system of industrial ecology is *increased market value of products* relative to material and energy consumption.

An industrial ecosystem can be set up using two basic complementary approaches. Within an industry, emphasis may be placed upon product durability and amenability to repair and recycle, which are compatible with the practice of industrial ecology. Instead of selling products, a concern may emphasize leasing so that it can facilitate recycling. The second approach emphasizes interactions between concerns so that they operate in keeping with good practice of industrial ecology. This approach facilitates materials and energy flow, exchange, and recycle between various firms in the industrial ecosystem.

An important aspect of an industrial ecosystem is the practice of a high degree of **industrial symbiosis**. Symbiotic relationships in natural biological systems occur when two often very dissimilar organisms live together in a mutually advantageous manner. Analogous symbiotic relationships in which firms utilize each other's residual materials form the basis of relationships between firms in a functional industrial ecosystem. Examples of industrial symbiosis are cited in Section 19.14 in the discussion of the Kalundborg, Denmark, industrial ecosystem.

A useful way to view an industrial ecosystem is geographically, often on the basis of a transportation network. An example is the Houston Ship Channel, which stretches for many kilometers and is bordered by a large number of petrochemical concerns that exist to mutual advantage through the exchange of materials and energy. The purification of natural gas by concerns located along the channel yields lower molecular mass hydrocarbons such as ethane and propane that can be used by other concerns, for example, in polymers manufacture. Sulfur removed from natural gas and petroleum can be used to manufacture sulfuric acid, which in turn is a key raw material for the manufacture of a number of other chemicals.

19.3 THE FIVE MAJOR COMPONENTS OF AN INDUSTRIAL ECOSYSTEM

Industrial ecosystems can be broadly defined to include all types of production, processing, and consumption. These include, for example, agricultural production as well as purely industrial operations. It is useful to define five major components of an industrial ecosystem, as shown in Figure 19.2. These are (1) a primary materials producer, (2) a source or sources of energy, (3) a materials processing and manufacturing sector, (4) a waste-processing sector, and (5) a consumer sector. In such an idealized system, the flow of materials among the four major hubs is very high. Each constituent of the system evolves in a manner that maximizes the efficiency with which the system utilizes materials and energy.

Primary Materials and Energy Producers

It is convenient to consider the primary materials producers and the energy generators together because both materials and energy are required for the industrial ecosystem to operate. The primary materials producer or producers may consist of one or several enterprises devoted to providing the basic materials that sustain the industrial ecosystem. Most generally, in any realistic industrial ecosystem a significant fraction of the material processed by the system consists of virgin materials. In a number of cases, and increasingly so as pressures build to recycle materials, significant amounts of the materials come from recycling sources.

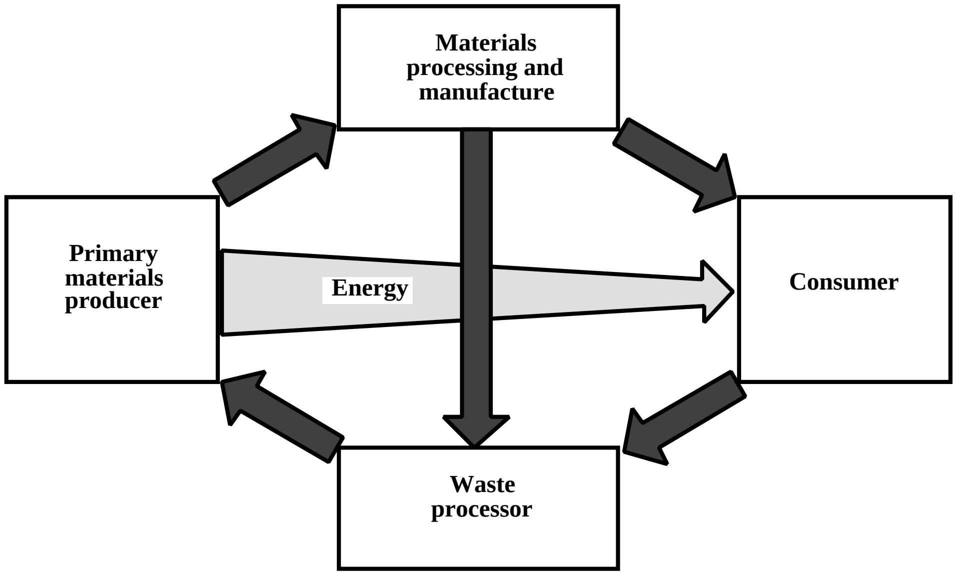

Figure 19.2 The major constituents or “hubs” of an industrial ecosystem.

The processes that virgin materials entering the system are subjected to vary with the kind of material, but can generally be divided into several major steps. Typically, the first step is **extraction**, designed to remove the desired substance as completely as possible from the other substances with which it occurs. This stage of materials processing can produce large quantities of waste material requiring disposal, as is the case with some metal ores in which the metal makes up a small percentage of the ore that is mined. In other cases, such as corn grain providing the basis of a corn products industry, the “waste,”—in this specific example the cornstalks associated with the grain—can be left in place (cornstalks returned to soil serve to add humus and improve soil quality). A **concentration** step may follow extraction to put the desired material into a purer form. After concentration, the material may be put through additional **refining** steps that may involve **separations**. Following these steps, the material is usually subjected to additional **processing** and **preparation** leading to the finished materials. Throughout the various steps of extraction, concentration, separation, refining, processing, preparation, and finishing, various physical and chemical operations are used, and wastes requiring disposal may be produced. Recycled materials may be introduced at various parts of the process, although they are usually introduced into the system following the concentration step.

The extraction and preparation of energy sources can follow many of the steps outlined above for the extraction and preparation of materials. For example, the processes involved in extracting uranium from ore, enriching it in the fissionable uranium-235 isotope, and casting it into fuel rods for nuclear fission power production include all of those outlined above for materials. On the other hand, some rich sources of coal are essentially scooped from a coal seam and sent to a power plant for power generation with only minimal processing, such as sorting and grinding.

Recycled materials added to the system at the primary materials and energy production phase may be from both pre- and postconsumer sources. As examples, recycled paper may be macerated and added at the pulping stage of paper manufacture. Recycled aluminum may be added at the molten metal stage of aluminum metal production.

Materials Processing and Manufacturing Sector

Finished materials from primary materials producers are fabricated to make products in the materials processing and manufacturing sector. This sector is often a very complex system. For example, the manufacture of an automobile requires steel for the frame, plastic for various components, rubber in tires, lead in the battery, copper in the wiring, and cloth or leather for the seats, along with a large number of other materials. Typically, the first step in materials manufacturing and processing is a forming operation. For example, sheet steel suitable for making automobile frames may be cut, pressed, and welded into the configuration needed to make a frame. At this step, some wastes may be produced that require disposal. An example of such wastes consists of carbon fiber/epoxy composites left over from forming parts such as jet aircraft engine housings. Finished components from the forming step are fabricated into finished products that are ready for the consumer market.

The materials processing and manufacturing sector presents several opportunities for recycling. At this point, it might be useful to define two different streams of recycled materials:

- **Process recycle streams** consisting of materials recycled in the manufacturing operation itself
- **External recycle streams** consisting of materials recycled from other manufacturers or from postconsumer products

Materials suitable for recycling can vary significantly. Generally, materials from the process recycle streams are quite suitable for recycling because they are the same materials used in the manufacturing operation. Recycled materials from the outside, especially those from postconsumer sources, may be quite variable in their characteristics because of the lack of effective controls over recycled postconsumer materials. Therefore, manufacturers may be reluctant to use such substances.

The Consumer Sector

In the consumer sector, products are sold or leased to the consumers who use them. The duration and intensity of use vary widely with the product; paper towels are used only once, whereas an automobile may be used thousands of times over many years. In all cases, however, the end of the useful lifetime of the product is reached and it is either (1) discarded or (2) recycled. The success of a total industrial ecology system can be measured largely by the degree to which recycling predominates over disposal.

Waste Processing Sector

Recycling has become so widely practiced that an entirely separate waste processing sector of an economic system can now be defined consisting of enterprises that deal specifically with the collection, separation, and processing of recyclable materials and their distribution to end users. Such operations may be entirely private or they may involve cooperative efforts with governmental sectors. They are often driven by laws and regulations as well as positive economic and regulatory incentives for their recycle.

19.4 INDUSTRIAL METABOLISM

Industrial metabolism in its entirety follows the flows of materials and energy from their initial sources through an industrial system, to the consumer, and to their ultimate disposal. In biological systems, metabolism can be studied at any level ranging from the molecular processes that occur in individual cells through the multiple processes and metabolic cycles that occur in individual organs, and to the overall process of metabolism that takes place in the whole organism. Similarly, industrial metabolism can be examined as individual unit operations within an industrial operation, at the factory level, at the industry level, and globally. For an industrial ecology approach, it is often most useful to view industrial metabolic processes at the regional level, large enough to have a number of industries with a variety of potential waste products that might be used by other industries, but small enough to permit transport and exchange of materials among various industries. To minimize pollution, it can be useful to consider units consisting of environmental domains, such as atmospheric basins or watersheds.

Unlike the living metabolic processes that occur in natural systems where true waste products are very rare, industrial metabolism as it is now practiced has a vexing tendency to dilute, degrade, and disperse materials to an extent that they are no longer useful but are still harmful to the environment. Indeed, waste has been defined as *dissipative use of natural resources*. In addition to simple loss from dilution and dispersion in the environment, materials may be lost by being tied up in low-energy forms or by being put into a chemical form from which they are very difficult to be retrieved.

An example of dissipation of material resulting in environmental pollution, now a very much diminished problem, was the widespread use of lead in tetraethyl lead antiknock additive in gasoline. The net result of this use was to disperse lead throughout the environment in auto exhaust gas, with no hope of recovery.

Industrial Metabolism and Biological Analogies

The strong analogy between natural ecosystems and efficient industrial systems was first clearly stated in 1989 by Frosch and Gallopoulos in an article in *Scientific American* cited under Supplementary References. A natural ecosystem, which is usually driven by solar energy and photosynthesis, consists of an assembly of mutually interacting organisms and their environment in which materials are interchanged in a largely cyclical manner. It is possible to visualize an analogous industrial ecosystem in which materials are cycled, driven by an energy source.

It is useful to view the metabolic processes of a natural ecosystem as a whole, rather than just observing each individual organism. Like a natural ecosystem, an industrial ecosystem synthesizes substances, thus performing anabolism, and it degrades substances, thereby performing in a manner analogous to biological catabolism. Typically, a large amount of a material, such as an ore or petroleum source, is metabolized to yield a relatively small quantity of a finished product. The objective of a properly designed and operated industrial ecosystem is to perform industrial metabolism in the most efficient manner possible so that the least possible raw material is used, the maximum amounts of materials are recycled through the system, and the most efficient possible use is made of the energy that sustains the industrial ecosystem.

An ideal biological ecosystem involves many organisms living in harmony with their environment without any net consumption of resources or production of waste products. The only input required for such an ecosystem is solar energy. This energy is captured and used by photosynthetic primary producers to convert carbon dioxide, water, and other inorganic materials into biomass. Herbivores ingest this biomass and use it for their energy and to synthesize their own biomass. Carnivores, of which there may be several levels, consume herbivores, and a food chain exists that may consist of several levels of organisms. Parasites exist on or in other organisms. Saprophytes and bacteria and fungi responsible for decay utilize and degrade biomass, eventually converting it back to simple inorganic constituents through the process of mineralization. Symbiotic and synergistic relationships abound in a natural ecosystem. Thus, an ideal ecosystem exists indefinitely in a steady-state condition without causing any net degradation of its environment.

A natural ecosystem can be visualized as having compartments in which various *stocks* of materials are kept, connected by *flows* of materials. Examples of such compartments include soil, which is a repository of plant nutrients; a body of water, such as a lake; and the atmosphere, which is a repository of carbon dioxide required for photosynthesis. In an undisturbed natural ecosystem, the quantities of the materials in each of these compartments remains relatively stable because such systems are inherently recycling. In contrast, the quantities of materials in the compartments of an industrial system are not constant. Reservoirs of raw materials, such as essential minerals, are constantly diminishing, although with new discoveries of mineral resources, they might *appear* to increase. Furthermore, reservoirs of wastes in an industrial system continually increase as materials traverse an essentially one-way path through the system. Sustainable industrial systems maximize recycling so that quantities of materials in the reservoirs remain constant as much as possible.

Systems of biological metabolism are **self-regulating**. At the level of the individual organism, regulation is accomplished internally by biological regulatory mechanisms, such as those that employ hormones. At the ecosystem level, regulation occurs through competition among organisms for available resources. In a manner analogous to natural ecosystems, industrial systems can be designed in principle to operate in a similar steady-state manner, ideally neither consuming nonrenewable resources nor producing useless waste products. Such systems can be self-regulating, with the economic system operating under the laws of supply and demand as the regulatory mechanism.

A comparison of the metabolisms of natural ecosystems with that of industrial systems as they are commonly encountered shows a marked contrast. These contrasts are highlighted in Table 19.1.

Table 19.1 Metabolic Characteristics of Natural Ecosystems and Industrial Systems

Characteristic	Natural ecosystems	Current industrial systems
Basic unit	Organism	Firm
Material pathways	Closed loops	Largely one-way
Recycling	Essentially complete	Often very low
Material fate	Tend to concentrate, such as atmospheric CO_2 converted to biomass by photosynthesis	Dissipative to produce materials too dilute to use, but concentrated enough to pollute
Reproduction	A major function of organisms is reproduction	Production of goods and services is the prime objective, not reproduction per se

Attractive as the idea may sound; in a modern society and especially in a "global economy," a complete industrial ecosystem carrying out industrial metabolism in an idealized fashion is not practical or even desirable. Essentially all modern communities produce at least one product that is exported to the outside, and must bring in materials and energy sources from elsewhere. A more realistic model of an industrial ecosystem is one in which raw materials are imported from the outside and at least one major product is exported from the system, but in which a number of enterprises coexist synergistically, utilizing each other's products and services to mutual advantage. In such a system, typically, raw materials flow into a primary raw material processor, which converts them to a processed material. The processed material then goes to one or more fabricators that make a product for distribution and sale. Associated with the enterprise as a whole are suppliers of a variety of materials, items, or services, and processors of secondary materials or wastes. To meet the criteria of an industrial ecosystem, as many of the byproducts and wastes as possible must be utilized and processed within the system.

Although industrial systems are self-regulating, they are not necessarily so in a manner conducive to sustainability; indeed, the opposite is frequently the case. Left to their own devices and operating under the principles of traditional economics, industrial systems tend toward a state of equilibrium or maximum entropy in which essential materials have been exploited, run through the system, and dissipated to the environment in dilute, useless, sometimes harmful forms. A central question is, therefore, the time scale on which this irreversible dissipation is allowed to occur. If it is a few decades, modern civilization is in real trouble; if it is on a scale of thousands of years, there is ample time to take corrective action to maintain sustainability. A challenge to modern industrialized societies is to modify industrial systems to maximize the time spans under which sustainability may be achieved.

19.5 LEVELS OF MATERIALS UTILIZATION

There are two extremes in levels of materials utilization in industrial systems. At the most inefficient level, as shown in Figure 19.3, raw materials are viewed as being unlimited and no consideration is given to limiting wastes. Such an approach was typical of industrial development in the U.S. in the 1800s and early 1900s when the prevailing view was that there were no limits to ores, fossil energy resources, and other kinds of raw materials; furthermore, it was generally held that the continent had an unlimited capacity to absorb industrial wastes.

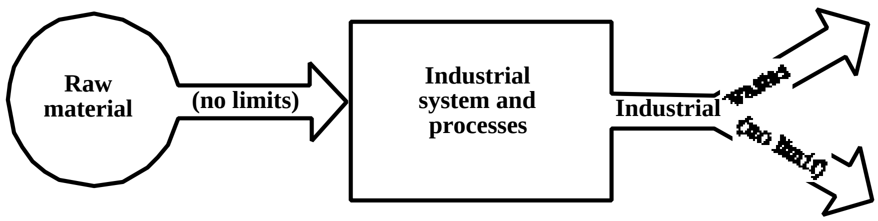

Figure 19.3 An industrial system without limits on either raw materials consumed or wastes produced.

A second kind of industrial system in which both raw materials and wastes are limited to greater or lesser extents is illustrated in Figure 19.4. Such a system has a relatively large circulation of materials within the industrial system as a whole, compared with reduced quantities of material going into the system and relatively lower production of wastes. Such systems are typical of those in industrialized nations and modern economic systems in which shortages of raw materials and limits to the places to put wastes are beginning to be felt. Even with such constraints, large quantities of materials are extracted, processed, and used, then either disposed of in the environment in concentrated form (hazardous wastes) or dispersed. In recent years, regulations and other constraints have markedly decreased point source pollution from industrial activity. However, because of the sheer volume of materials processed through industrial societies, dissipative pollution continues to be a problem.

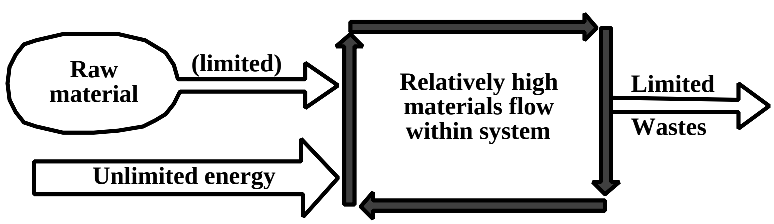

Figure 19.4 Illustration of an industrial system in which both the utilization of raw materials and the production of wastes are limited to a certain degree.

An industrial ecosystem with no materials input and no wastes is illustrated in Figure 19.5. The material flows within the system itself are quite high. In addition, the energy requirements of such a system can be rather high, and a key to its successful operation is often an abundant, minimally polluting primary source of energy. Such a system is an idealized one that can never be realized in practice, but it serves as a useful goal around which more-practical and achievable systems can be based.

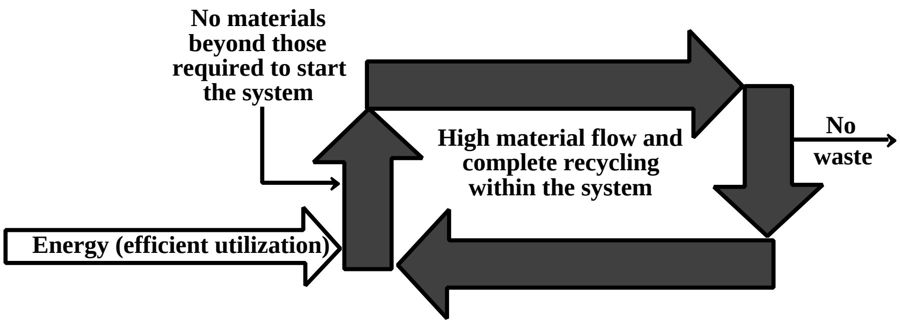

Figure 19.5 Idealized industrial ecosystem in which no materials are required for input beyond those needed to start the system. Energy requirements are relatively high, and the material flow within the system is high and continuous.

19.6 LINKS TO OTHER ENVIRONMENTAL SPHERES

Having addressed industrial ecology largely from the anthrospheric viewpoint, it is now appropriate to consider how the anthrosphere and the practice of indus-rial ecology influence the other four spheres of the environment—the atmosphere, the hydrosphere, the geosphere, and the biosphere. Influences of industrial activities, broadly defined to include energy and agricultural production as well as manufacture of goods and provision of essential services, can range from minor effects all the way up to major perturbations of the environment that may pose significant threats to Earth's ability to support life. Such influences can range from highly localized ones occurring for only a brief period of time to global effects that have the potential to last for centuries. An example of the former would be an isolated incident of water pollution by oxygen-consuming organic matter in a reservoir. The damage is often confined to the reservoir and only for the relatively short period of time required to degrade the wastes and replenish the oxygen supply. The prime example of a long-term global effect is the emission of greenhouse gases, which has the potential to change Earth's entire climate for thousands of years. An effect of intermediate duration is contamination of the atmosphere with ozone-destroying chlorofluorocarbons (Chapter 16, Section 16.4), an effect that will last for several decades after release of these substances has been stopped.

The major goal of industrial ecology, therefore, must be to minimize or eliminate detrimental effects of anthrospheric activities on other spheres of the environment. Beyond environmental preservation, the practice of industrial ecology should also improve and enhance environmental conditions. Listed below are the major anthrospheric activities along with their potential effects on other environmental spheres.

Fossil fuel combustion

Atmosphere: The greatest potential effect is greenhouse warming. Emission of partially combusted hydrocarbons and nitrogen oxides can cause formation of photochemical oxidants (photochemical smog). Acid precipitation may be caused by emissions of sulfur oxides from fuel combustion. General deterioration of atmospheric quality may occur through reduced visibility.

Hydrosphere: The potential exists for water pollution from acid mine water, petroleum production by-product brines, acid precipitation, and heating of water used to cool power plants.

Geosphere: The greatest potential effects are disturbance of land from coal mining.

Biosphere: Most effects are indirect as the result of influences on the atmosphere, hydrosphere, and geosphere.

Industrial manufacturing and processing

Atmosphere: Greatest potential effects are due to emissions of gases, vapors, and particles. These include greenhouse gases, acid gases, particles, precursors to photochemical smog formation, and species with the potential to deplete stratospheric ozone.

Hydrosphere: Industrial activities can contaminate water with a variety of pollutants. Consumptive uses of water may put pressure on limited water supplies, especially in arid regions. Water used for cooling may be thermally polluted.

Geosphere: The greatest effect results from the extractive industries through which minerals are recovered. The geosphere may be contaminated by solid and hazardous wastes, and available landfill space may become depleted.

Biosphere: The greatest direct effect is from the distribution of toxic substances as the result of industrial activities. There may also be significant indirect effects resulting from deterioration of the atmosphere, hydrosphere, and geosphere.

Crop production

Atmosphere: A major potential effect is emission of greenhouse gases as the result of deforestation and "slash and burn" agriculture to grow more crops. Significant amounts of greenhouse gas methane are emitted into the atmosphere as the result of methane-generating bacteria growing in rice paddies.

Hydrosphere: Large quantities of water are used for irrigation. Some of the water is lost by transpiration from plants, and some by infiltration to groundwater. Water returned to the hydrosphere from irrigation may have an excessively high salinity. Surface water and groundwater may become contaminated by solids, fertilizers, and herbicides from crop production.

Geosphere: Large areas of the geosphere may be disturbed by cultivation to produce crops. Topsoil can be lost from water and wind erosion. Proper agricultural practices, such as contour farming and low-tillage agriculture, minimize these effects and might even enhance soil quality.

Biosphere: Organisms are profoundly affected by agricultural practices designed to produce crops. Entire ecosystems are destroyed and replaced by other “anthrospheric” ecosystems. The greatest effect on the biosphere is loss of species diversity from the destruction of natural ecosystems, and from the cultivation of only limited strains of crops.

Livestock production (domestic animals)

Atmosphere: Ruminant animals are significant producers of greenhouse gas methane as the result of methane-producing bacteria in their digestive systems.

Hydrosphere: Livestock production requires large quantities of water. Large amounts of oxygen-consuming wastes that might contaminate surface water are produced by livestock. Nitrogen wastes from the manure and urine of animals in feedlots may cause nitrate contamination of groundwater.

Geosphere: The production of a unit mass of food from livestock sources requires much more crop production than is required for grains consumed directly by humans. A major impetus behind destruction of rain forests has been to grow forage and other foods for livestock. Rangeland has deteriorated because of overgrazing.

Biosphere: A major effect is loss of species diversity. This occurs even within domestic strains of livestock where modern breeding practices have resulted in the loss of entire breeds of livestock. The ultimate loss of domestic diversity occurs when animals are cloned.

The most environmentally damaging effects of human activities are those that are cumulative. As noted previously, the most significant of these at present is likely the accumulation of greenhouse gases that have the potential to cause global warming. Some environmental problems, such as those resulting from the emission of photochemical smog-forming pollutants into the atmosphere are potentially reversible. However, by the time global warming has been demonstrated to be a genuine problem, if such turns out to be the case, the damage will have been done, and little, if anything, will be able to reverse it.

19.7 CONSIDERATION OF ENVIRONMENTAL IMPACTS IN INDUSTRIAL ECOLOGY

By its nature, industrial production has an impact upon the environment. Whenever raw materials are extracted, processed, used, and eventually discarded, some environmental impacts will occur. In designing an industrial ecological system, several major kinds of environmental impacts must be considered in order to minimize them and keep them within acceptable limits. These impacts and the measures taken to alleviate them are discussed below.

For most industrial processes, the first environmental impact is that of extracting raw materials. This can be a straightforward case of mineral extraction, or it can be less direct, such as utilization of biomass grown on forest or crop land. A basic decision, therefore, is the choice of the kind of material to be used. Wherever possible, materials should be chosen that are not likely to be in short supply in the foreseeable future. As an example, the silica used to make the lines employed for fiber-optics communication is in unlimited supply and a much better choice for communication lines than copper wire made from limited supplies of copper ore.

Industrial ecology systems should be designed to reduce or even totally eliminate air pollutant emissions. Among the most notable recent progress in that area has been the marked reduction and even total elimination of solvent vapor emissions (volatile organic carbon, VOC), particularly those from organochlorine solvents. Some progress in this area has been made with more-effective trapping of solvent vapors. In other cases, the use of the solvents has been totally eliminated. This is the case for chlorofluorocarbons (CFCs), which are no longer used in plastic foam blowing and parts cleaning because of their potential to affect stratospheric ozone. Other air pollutant emissions that should be eliminated are hydrocarbon vapors, including those of methane, CH_4, and oxides of nitrogen or sulfur.

Discharges of water pollutants should be entirely eliminated wherever possible. For many decades, efficient and effective water treatment systems have been employed that minimize water pollution. However, these are “end of pipe” measures, and it is much more desirable to design industrial systems such that potential water pollutants are not even generated.

Industrial operations should be designed to prevent production of liquid water-based or organic solvent-based wastes that may have to be sent to a waste processor. Under current conditions, the largest single constituent of so-called “hazardous wastes” is water. Elimination of water from the waste stream automatically prevents pollution and reduces amounts of wastes requiring disposal. The solvents in organic wastes largely represent potentially recyclable or combustible constituents. A properly designed industrial ecosystem does not allow such wastes to be generated or to leave the factory site.

In addition to liquid wastes, many solid wastes must be considered in an industrial ecosystem. The most troublesome are toxic solids that must be placed in a secure hazardous-waste landfill. The problem has become especially acute in some industrialized nations in which the availability of landfill space is severely limited. In a general sense, solid wastes are simply resources that have not been properly utilized. Closer cooperation among suppliers, manufacturers, consumers, regulators, and recyclers can minimize quantities and hazards of solid wastes.

Whenever energy is expended, there is a degree of environmental damage. Therefore, energy efficiency has a high priority in a properly designed industrial ecosystem. Significant progress has been made in this area in recent decades, as much because of the high costs of energy as for environmental improvement. More-efficient devices, such as electric motors, and approaches, such as congeneration of electricity and heat, that make the best possible use of energy resources are highly favored. An important side benefit of more-efficient energy utilization is the lowered emissions of air pollutants, including greenhouse gases.

19.8 THREE KEY ATTRIBUTES: ENERGY, MATERIALS, DIVERSITY

By analogy with biological ecosystems, a successful industrial ecosystem should have (1) renewable energy, (2) complete recyling of materials, and (3) species diversity for resistance to external shocks. These three key characteristics of industrial ecosystems are addressed here.

Unlimited Energy

Energy is obviously a key ingredient of an industrial ecosystem. Unlike materials, the flow of energy in even a well-balanced closed industrial ecosystem is essentially one-way in that energy enters in a concentrated, highly usable form, such as chemical energy in natural gas, and leaves in a dilute, disperse form as waste heat. An exception is the energy that is stored in materials. This can be in the form of energy that can be obtained from materials, such as by burning rubber tires, or it can be in the form of what might be called “energy credit,” which means that by using a material in its refined form, energy is not consumed in making the material from its raw material precursors. A prime example of this is the “energy credit” in metals, such as that in aluminum metal, which can be refined into new aluminum objects requiring only a fraction of the energy consumed to refine the metal from aluminum ore. On the other hand, recycling and reclaiming some materials can require a lot of energy, and the energy consumption of a good closed industrial ecosystem can be rather high.

Given the needed elements, any material can be made if a sufficient amount of energy is available. The key energy requirement is a source that is abundant and of high quality, that can be used efficiently, and that does not produce unacceptable by-products.

Although energy is ultimately dissipated from an industrial ecosystem, it may go through two or more levels of use before it is wasted. An example of this would be energy from natural gas burned in a turbine linked to a generator, the exhaust gases used to raise steam in a power plant to run a steam turbine, and the relatively cool steam from the turbine used to heat buildings.

Natural ecosystems run on unlimited, renewable energy from the sun or, in some specialized cases, from geochemical sources. Successful industrial ecosystems must also have sources of energy that are not severely limited by either supply or potential for environmental damage in order to be sustained for an indefinite period of time. The obvious choice for such an energy source would seem to be solar energy. However, solar sources present formidable problems, not the least of which is that they work poorly during those times of the day and seasons of the year when the sun does not shine. Even under optimum conditions, solar energy has a low power density necessitating collection and distribution systems of an unprecedented scale if they are going to displace present fossil energy sources. Other renewable sources, such as wind, tidal, geothermal, biomass, and hydropower present similar challenges. It is likely, therefore, that fossil energy sources will provide a large share of the energy for industrial ecosystems in the foreseeable future. This assumes that a way can be found to manage greenhouse gases. At the present time, it appears that injection of carbon dioxide from combustion into deep ocean regions is the only viable alternative for sequestering carbon dioxide, and this approach remains an unproven technology on a large scale. (One potential problem is that the slight increase in ocean water pH of about $^{1}/_{10}$ pH unit could be detrimental to many of the organisms that live in the ocean.)

Nuclear fusion power remains a tantalizing possibility for unlimited energy, but so far practical nuclear fusion reactors for power generation have proven an elusive target. Unattractive as it is to many, the only certain, environmentally acceptable energy source that can without question fill the energy needs of modern industrial ecology systems is nuclear fission energy. With breeder reactors that can generate additionalfissionable material from essentially unlimited supplies of uranium-238, nuclear fission can meet humankind's energy needs for the foreseeable future. Of course, there are problems with nuclear fission—more political and regulatory than technical. The solution to these problems remains a central challenge for humans in the modern era.

Industrial Ecology and Material Resources

A system of industrial ecology is successful if it reduces demand for materials from virgin sources. Strategies for reduced material use may be driven by technology, by economics, or by regulation. The four major ways in which material consumption can be reduced are (1) using less of a material for a specific application, an approach called **dematerialization**; (2) **substitution** of a relatively more abundant and safe material for one that is scarce or toxic; (3) **recycling**, broadly defined; and (4) extraction of useful materials from wastes, sometimes called **waste mining**. These four facets of efficient materials utilization are outlined in this section.

Dematerialization

There are numerous recent examples of reduced uses of materials for specific applications. One example of dematerialization is the transmission of greater electrical power loads with less copper wire by using higher voltages on long distance transmission lines. Copper is also used much more efficiently for communications transmission than it was in the early days of telegraphy and telephone communication. Amounts of silver used per roll of photographic film have decreased significantly in recent years. The layer of tin plated onto the surface of a "tin can" used for food preservation and storage is much lower now than it was several decades ago. In response to the need for greater fuel economy, the quantities of materials used in automobiles have decreased significantly over the last 2 decades, a trend reversed, unfortunately, by the more recent increased popularity of large "sport utility vehicles." Automobile storage batteries now use much less lead for the same amount of capacity than they did in former years. The switch from 6-volt to 12-volt auto batteries in the 1950s enabled use of lighter wires, such as those from the battery to the electrical starter. Somewhat later, the change to steel-belted radial tires enabled use of lighter tires and resulted in greatly increased tire lifetimes so that much less rubber was used for tires.

One of the most commonly cited examples of dematerialization is that resulting from the change from vacuum tubes to solid state circuit devices. Actually, this conversion should be regarded as material substitution, as transistors replaced vacuum tubes, followed by spectacular mass reductions as solid state circuit technology advanced.

Dematerialization can be expected to continue as technical advances, some rapid and spectacular, others slow and incremental, continue to be made. Some industries lead the way out of necessity. Aircraft weight has always played a crucial role in determining performance, so the aircraft manufacturing sector is one of the leaders in dematerialization.

Substitution of Materials

Substitution and dematerialization are complementary approaches to reducing materials use. The substitution of solid state components for electronic vacuum tubes and the accompanying reduction in material quantities has already been cited. The substitution of polyvinylchloride (PVC) siding in place of wood on houses has resulted in dematerialization over the long term because the plastic siding does not require paint.

Technology and economics combined have been leading factors in materials substitution. For example, the technology to make PVC pipe for water and drain lines has enabled its use in place of more expensive cast iron, copper, and even lead pipe (in the last case, toxicity from lead contamination of water is also a factor to be considered).

A very significant substitution that has taken place over recent decades is that of aluminum for copper and other substances. Copper, although not a strategically short metal resource, nevertheless is not one of the more abundant metals in relation to the demand for it. Considering its abundance in the geosphere and in sources such as coal ash, aluminum is a very abundant metal. Now aluminum is used in place of copper in many high voltage electrical transmission applications. Aluminum is also used in place of brass, a copper-containing alloy, in a number of applications. Aluminum roofing substitutes for copper in building construction. Aluminum cans are used for beverages in place of tin-plated steel cans.

There have been a number of subsitutions of chemicals in recent years, many of them driven by environmental concerns and regulations resulting from those concerns. One of the greater of these has been the substitution of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) for chlorofluorocarbons (Freons or CFCs) driven by concerns over stratospheric ozone depletion. Substitutions of nonhalogenated solvents, supercritical fluid carbon dioxide, and even water with appropriate additives for chlorinated hydrocarbon solvents will continue as environmental concerns over these solvents increase.

Substitutions for metal-containing chemicals promise to reduce costs and toxicities. One such substitution that has greatly reduced the possibilities for lead poisoning is the use of titanium-based pigments in place of lead for white paints. In addition to lead, cadmium, chromium, and zinc are also used in pigments, and substitution of organic pigments for these metals in paints has reduced toxicity risks. Copper, chromium, and arsenic are used in treated wood (CCA lumber). Because of the toxicity of arsenic, particularly, it would be advisable to develop substitutes for these metals in wood. It should be pointed out, however, that the production of practically indestructible CCA lumber has resulted in much less use of wood, and has saved the materials and energy required to replace wood that has rotted or been damaged by termites.

Recycling

For a true and complete industrial ecosystem, close to 100% recycling of materials must be realized. In principle, given a finite supply of all the required elements and abundant energy, essentially complete recycling can be achieved. A central goal of industrial ecology is to develop efficient technologies for recycling that reduce the need for virgin materials to the lowest possible levels. Another goal must be to implement process changes that eliminate dissipative uses of toxic substances, such as heavy metals, that are not biodegradable and that pose a threat to the environment when they are discarded.

For consideration of recycling, matter can be put into four separate categories. The first of these consists of elements that occur abundantly and naturally in essentially unlimited quantities in consumable products. Food is the ultimate consumable product. Soap is consumed for cleaning purposes, discarded down the drain, precipitated as its insoluble calcium salt, then finally biodegraded. Materials in this category of recyclables are discharged into the environment and recycled through natural processes or for very low-value applications, such as sewage sludge used as fertilizer on soil.

A second category of recyclable materials consists of elements that are not in short supply, but are in a form that is especially amenable to recycling. Wood is one such commodity. At least a portion of wood taken from buildings that are being razed could and should be recycled. The best example of a kind of commodity in this class is paper. Paper fibers can be recycled up to five times, and the nature of paper is such that it is readily recycled. More than 1/3 of world paper production is currently from recycled sources, and that fraction should exceed 50% within the next several decades. The major impetus for paper recycling is not a shortage of wood to make virgin paper, but rather a shortage of landfill space for waste paper.

A third category of recyclables consists of those elements, mostly metals, for which world resources are low. Chromium and the platinum group of precious metals are examples of such elements. Given maximum incentives to recycle, especially through the mechanism of higher prices, it is likely that virgin sources of these metals can make up any shortfall not met by recycling in the foreseeable future.

A fourth category of materials to consider for recycling consists of parts and apparatus, such as auto parts discussed previously. In many cases, such parts can be refurbished and reused. Even when this is not the case, substantial monetary deposits collected from customers at the time of purchase can provide incentives for recycling. For components to be recycled efficiently and easily, they must be designed with reuse in mind in aspects such as facile disassembly. Such an approach has been called “design for environment,” DFE, and is discussed in more detail in Section 19.10.

Combustion to produce energy can be a form of recycling. For some kinds of materials, combustion in a power plant is the most cost-effective and environmentally safe way of dealing with materials. This is true, for example, of municipal refuse that contains a significant energy value because of combustible materials in it as well as a variety of items that potentially could be recycled for the materials in them. However, once such items become mixed in municipal refuse and contaminated with impurities, the best means of dealing with them is simply combustion.

It should be noted that recycling comes with its own set of environmental concerns. One of the greatest of these is contamination of recycled materials with toxic substances. In some cases, motor oil, especially that collected from the individual consumer sector, can be contaminated with organohalide solvents and other troublesome impurities. Food containers pick up an array of contaminants and, as a consequence, recycled plastic is not generally regarded as a good material for food applications. Substances may become so mixed with use that recycling is not practical. This occurs particularly with synthetic fibers, but it may be a problem with plastics, glass, and other kinds of recyclable materials.

Extraction of Useful Materials from Wastes

Sometimes called waste mining, the extraction of useful materials from wastes has some significant, largely unrealized potential for the reduction in use of virgin materials. Waste mining can often take advantage of the costs that must necessarily be incurred in treating wastes, such as flue gases. Sulfur is one of the best examples of a material that is now commonly recovered from wastes. Sulfur is a constituent of all coal and can be recovered from flue gas produced by coal combustion. It would not be cost-effective to use flue gas simply as a source of sulfur. However, since removal of sulfur dioxide from flue gas is now required by regulation, the incremental cost of recovering sulfur as a commodity, rather than simply discarding it, can make sulfur recovery economically feasible.

There are several advantages to recovering a useful resource from wastes. One of these is the reduced need to extract the resource from a primary source. Therefore, every kilogram of sulfur recovered from flue gas means one less kg of sulfur that must be extracted from sulfur ore sources. By using waste sources, the primary source is preserved for future use. Another advantage is that extraction of a resource from a waste stream can reduce the toxicity or potential environmental harm from the waste stream. The removal of arsenic byproduct from the residues of refining some metals that occur with arsenic significantly reduces the toxicities and potential environmental harm by the wastes. Coal ash, the residue remaining after the combustion of coal for power generation, could be used as a source of iron (ferrosilicon), silicon, and aluminum, and perhaps several other elements as well. An advantage of using coal ash in such applications is its physical form. For most power applications, the feed coal is finely ground, so that the ash is in the form of a powder. This means that coal ash is already in the physical form most amenable to processing for byproducts recovery. For a particular coal feedstock, coal ash is homogeneous, which offers some definite advantages in processing and resource recovery. A third advantage of coal ash is that it is anhydrous, so no additional energy needs to be expended in removing water from an ore.

Diversity and Robust Character of Industrial Ecosystems

Successful natural ecosystems are highly diverse, as a consequence of which they are also very **robust**. Robustness means that if one part of the system is perturbed, there are others that can take its place. Consider what happens if the numbers of a top predator at the top of a food chain in a natural ecosystem are severely reduced because of disease. If the system is well balanced, another top predator is available to take its place.

The energy sector of industrial ecosystems often suffers from a lack of robustness. Examples of energy vulnerability have become obvious with several “energy crises” during recent history. Another requirement of a healthy industrial ecology system that is vulnerable in some societies is water. In some regions of the world, both the quantity and quality of water are severely limited. A lack of self-sufficiency in food is a third example of vulnerability. Vulnerabililty in food and water are both strongly dependent upon climate, which in turn is tied to environmental concerns as a whole.

19.9 LIFE CYCLES: EXPANDING AND CLOSING THE MATERIALS LOOP

In a general sense, the traditional view of product utilization is the one-way process of extraction → production → consumption → disposal shown in the upper portion of Figure 19.6. Materials that are extracted and refined are incorporated into the production of useful items, usually by processes that produce large quant-ities of waste by-products. After the products are worn out, they are discarded. This essentially one-way path results in a relatively large exploitation of resources, such as metal ores, and a constant accumulation of wastes. As shown at the bottom of Figure 19.6, however, the one-way path outlined above can become a cycle in which manufactured goods are used, then recycled at the end of their life spans. As

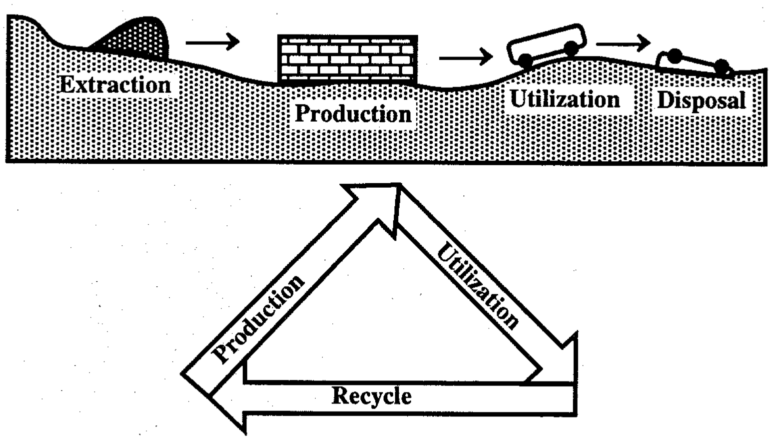

Figure 19.6 The one-way path of conventional utilization of resources to make manufactured goods followed by disposal of the materials and goods at the end consumes large quantities of materials and makes large quantities of wastes (top). In an ideal industrial ecosystem (bottom), the loop is closed and spent products are recycled to the production phase.

one aspect of such a cyclic system, it is often useful for manufacturers to assume responsibility for their products, to maintain “stewardship.” Ideally, in such a system a product or the material in it would have a never-ending life cycle; when its useful lifetime is exhausted, it is either refurbished or converted into another product.

In considering life cycles, it is important to note that commerce can be divided into the two broad categories of **products** and **services**. Whereas most commercial activity used to be concentrated on providing large quantities of goods and products, demand has been largely satisfied for some segments of the population, and the wealthier economies are moving more to a service-based system. Much of the commerce required for a modern society consists of a mixture of services and goods. The trend toward a service economy offers two major advantages with respect to wasteminimization. Obviously, a pure service involves little material, and a service provider is in a much better position to control materials to ensure that they are recycled and to control wastes, ensuring their proper disposal. A commonly cited example is that of photocopy machines. They provide a service, and a heavily used copy machine requires frequent maintenance and cleaning. The parts of such a machine and the consumables, such as toner cartridges, consist of materials that eventually will have to be discarded or recycled. In this case, it is often reasonable for the provider to lease the machine to users, taking responsibility for its maintenance and ultimate fate. The idea could even be expanded to include recycling of the paper processed by the copier, with the provider taking responsibility for recyclable paper processed by the machine.

It is usually difficult to recycle products or materials within a single, relatively narrow industry. In most cases, to be practical, recycling must be practiced on a larger scale than simply that of a single industry or product. For example, recycling plastics used in soft drink bottles to make new soft drink bottles is not allowed because of the possibilities for contamination. However, the plastics can be used as raw material for auto parts. Usually, different companies are involved in making auto parts and soft drink bottles.

Product Stewardship

The degree to which products are recycled is strongly affected by the custody of the products. For example, batteries containing cadmium or mercury pose significant pollution problems when they are purchased by the public; used in a variety of devices, such as calculators and cameras; then discarded through a number of channels, including municipal refuse. However, when such batteries are used within a single organization, it is possible to ensure that almost all of them are returned for recycling. In cases such as this, systems of stewardship can be devised in which marketers and manufacturers exercise a high degree of control of the product. This can be done through several means. One is for the manufacturer to retain ownership of the product, as is commonly practiced with photocopy machines. Another mechanism is one in which a significant part of the purchase price is refunded for trade-in of a spent item. This approach could work very well with batteries containing cadmium or mercury. The normal purchase price could be doubled, then discounted to half with the trade-in of a spent battery.

Embedded Utility

Figure 19.7 can be regarded as an “energy/materials pyramid” showing that the amounts of energy and materials involved decrease going from the raw material to the finished product. The implication of this diagram is that significantly less energy, and certainly no more materials, are involved when recycling is performed near the top of the materials flow chain rather than near the bottom.

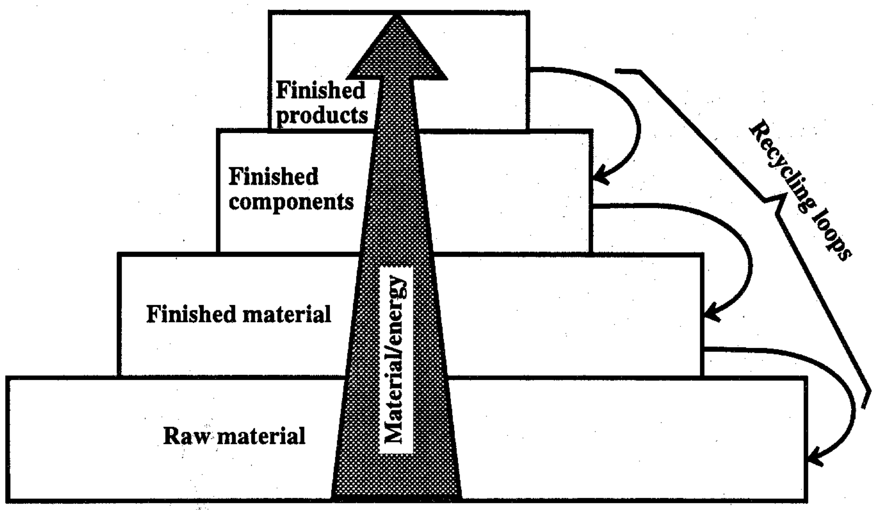

Figure 19.7 A material flow chain or energy/materials pyramid. Less energy and materials are involved when recycling is done near the end of the flow chain, thus retaining embedded utility.

To give a simple example, relatively little energy is required to return a glass beverage bottle from the consumer to the bottler, whereas returning the bottle to the glass manufacturer where it must be melted down and refabricated as a glass container obviously takes a greater amount of energy.

From a thermodynamic standpoint, a final product is relatively more ordered and it is certainly more usable for its intended purpose. The greater usability and lower energy requirements for recycling products higher in the order of material flow are called **embedded utility**. One of the major objectives of a system of industrial ecology and, therefore, one of the main reasons for performing life-cycle assessments is to retain the embedded utility in products by measures such as recycling as near to the end of the material flow as possible, and replacing only those components of systems that are worn out or obsolete. An example of the latter occurred during the 1960s when efficient and safe turboprop engines were retrofitted to still-serviceable commercial aircraft airframes to replace complex piston engines, thus extending the lifetime of the aircraft by a decade or more.

19.10 LIFE-CYCLE ASSESSMENT

From the beginning, industrial ecology must consider process/product design in the management of materials, including the ultimate fates of materials when they are discarded. The product and materials in it should be subjected to an entire **life-cycle assessment** or analysis. A life-cycle assessment applies to products, processes, and services through their entire life cycles from extraction of raw materials—through manufacturing, distribution, and use—to their final fates from the viewpoint of determining, quantifying, and ultimately minimizing their environmental impacts. It takes account of manufacturing, distribution, use, recycling, and disposal. Life-cycle assessment is particularly useful in determining the relative environmental merits of alternative products and services. At the consumer level, this could consist of an evaluation of paper versus styrofoam drinking cups. On an industrial scale, life-cycle assessment could involve evaluation of nuclear versus fossil energy-based electrical power plants.

A basic step in life-cycle analysis is **inventory analysis** which provides qualitative and quantitative information regarding consumption of material and energy resources (at the beginning of the cycle) and releases to the anthrosphere, hydrosphere, geosphere, and atmosphere (during or at the end of the cycle). It is based upon various materials cycles and budgets, and it quantifies materials and energy required as input and the benefits and liabilities posed by products. The related area of **impact analysis** provides information about the kind and degree of environmental impacts resulting from a complete life cycle of a product or activity. Once the environmental and resource impacts have been evaluated, it is possible to do an **improvement analysis** to determine measures that can be taken to reduce impacts on the environment or resources.

In making a life-cycle analysis the following must be considered:

- If there is a choice, selection of the kinds of materials that will minimize waste
- Kinds of materials that can be reused or recycled
- Components that can be recycled
- Alternate pathways for the manufacturing process or for various parts of it

Although a complete life-cycle analysis is expensive and time-consuming, it can yield significant returns in lowering environmental impacts, conserving resources, and reducing costs. This is especially true if the analysis is performed at an early stage in the development of a product or service. Improved computerized techniques are making significant advances in the ease and efficacy of life-cycle analyses. Until now, life-cycle assessments have been largely confined to simple materials and products such as reusable cloth vs. disposable paper diapers. A major challenge now is to expand these efforts to more-complex products and systems such as aircraft or electronics products.

Scoping in Life-Cycle Assessment

A crucial early step in life-cycle assessment is **scoping** the process by determining the boundaries of time, space, materials, processes, and products to be considered. Consider as an example the manufacture of parts that are rinsed with an organochloride solvent in which some solvent is lost by evaporation to the atmosphere, by staying on the parts, during the distillation and purification process by which the solvent is made suitable for recycling, and by disposal of waste solvent that cannot be repurified. The scope of the life-cycle assessment could be made very narrow by confining it to the process as it exists. An assessment could be made of the solvent losses, the impacts of these losses, and means for reducing the losses, such as reducing solvent emissions to the atmosphere by installation of activated carbon air filters or reducing losses during purification by employing more-efficient distillation processes. A more broadly scoped life-cycle assessment would consider alternatives to the organochloride solvent. An even broader scope would consider whether the parts even need to be manufactured—are there alternatives to their use?

19.11 CONSUMABLE, RECYCLABLE, AND SERVICE (DURABLE) PRODUCTS

In industrial ecology, most treatments of life-cycle analysis make the distinction between **consumable products**, which are essentially used up and dispersed to the environment during their life cycle and **service or durable products**, which essentially remain in their original form after use. Gasoline is clearly a consumable product, whereas the automobile in which it is burned is a service product. It is useful, however, to define a third category of products that clearly become "worn out" when employed for their intended purpose, but which remain largely undispersed to the environment. The motor oil used in an automobile is such a substance in that most of the original material remains after use. Such a category of material may be called a **recyclable commodity**.

Desirable Characteristics of Consumables

Consumable products include laundry detergents, hand soaps, cosmetics, windshield washer fluids, fertilizers, pesticides, laser printer toners, and all other materials that are impossible to reclaim after they are used. The environmental implications of the use of consumables are many and profound. In the late 1960s and early 1970s, for example, nondegradable surfactants in detergents caused severe foaming and esthetic problems at water treatment plants and sewage outflows, and the phosphate builders in the detergents promoted excessive algal growth in receiving waters, resulting in a condition known as eutrophication. Lead in consumable leaded gasoline was widely dispersed to the environment when the gasoline was burned. These problems have now been remedied with the adoption of phosphate-free detergents employing biodegradable surfactants and the mandatory use of unleaded gasoline.

Since they are destined to be dispersed into the environment, consumables should meet several "environmentally friendly" criteria, including the following:

- **Degradability**. This usually means biodegradability, such as that of household detergent constituents that occurs in waste-treatment plants and in the environment. Chemical degradation may also occur.
- **Nonbioaccumulative**. Lipid-soluble, poorly biodegradable substances, such as DDT and PCBs, tend to accumulate in organisms and to be magnified through the food chain. This characteristic should be avoided in consumable substances.
- **Nontoxic**. To the extent possible, consumables should not be toxic in the concentrations that organisms are likely to be exposed to them. In addition to their not being acutely toxic, consumables should not be mutagenic, carcinogenic, or teratogenic (cause birth defects).

Desirable Characteristics of Recyclables

Recyclables is used here to describe materials that are not used up in the sense that laundry detergents or photocopier toners are consumed, but are not durable items. Recyclables can consist of a variety of chemical substances and formulations. The hydrochlorofluorocarbons (HCFCs) used as refrigerant fluids fall into this category, as does ethylene glycol mixed with water in automobile engine antifreeze/antiboil formulations (although rarely recycled in practice).

Insofar as possible, recyclables should be minimally hazardous with respect to toxicity, flammability, and other hazards. For example, both volatile hydrocarbon solvents and organochloride (chlorinated hydrocarbon) solvents are recyclable after use for parts degreasing and other applications requiring a good solvent for organic materials. The hydrocarbon solvents have relatively low toxicities, but may present flammability hazards during use and reclamation for recycling. The organochloride solvents are less flammable, but may present a greater toxicity hazard. An example of such a solvent is carbon tetrachloride, which is so nonflammable that it was once used in fire extinguishers, but the current applications of which are highly constrained because of its high toxicity.

An obviously important characteristic of recyclables is that they should be designed and formulated to be amenable to recycling. In some cases, there is little leeway in formulating potentially recyclable materials; motor oil, for example, must meet certain criteria, including the ability to lubricate, stand up to high temperatures, and other attributes, regardless of its ultimate fate. In other cases, formulations can be modified to enhance recyclability. For example, the use of bleachable or removable ink in newspapers enhances the recyclability of the newsprint, enabling it to be restored to an acceptable level of brightness.

For some commodities, the potential for recycling is enormous. This can be exemplified by lubricating oils. The volume of motor oil sold in the U.S. each year for gasoline engines is about 2.5 billion liters, a figure that is doubled if all lubricating oils are considered. A particularly important aspect of utilizing recyclables is their collection. In the case of motor oil, collection rates are low from consumers who change their own oil, and they are responsible for the dispersion of large amounts of waste oil to the environment.

Desirable Characteristics of Service Products

Since, in principle at least, service products are destined for recycling, they have comparatively lower constraints on materials and higher constraints on their ultimate disposal. A major impediment to the recycling of service products is the lack of convenient channels through which they can be put into the recycling loop. Television sets and major appliances such as washing machines or ovens have many recyclable components, but often end up in landfills and waste dumps simply because there is no handy means for getting them from the user and into the recycling loop. In such cases, government intervention may be necessary to provide appropriate channels. One partial remedy to the disposal/recycling problem consists of leasing arrangements or payment of deposits on items such as batteries to ensure their return to a recycler. The terms “de-shopping” or “reverse shopping” describe a process by which service commodities would be returned to a location such as a parking lot where they could be collected for recycling. According to this scenario, the analogy to a supermarket would be a facility in which service products are disassembled for recycling.

Much can be done in the design of service products to facilitate their recycle. One of the main characteristics of recyclable service products must be ease of disassembly so that remanufacturable components and recyclable materials, such as copper wire, can be readily removed and separated for recycling.

19.12 DESIGN FOR ENVIRONMENT

Design for environment is the term given to the approach of designing and engineering products, processes, and facilities in a manner that minimizes their adverse environmental impacts and, where possible, maximizes their beneficial environmental effects. In modern industrial operations, design for environment is part of a larger scheme termed “design for X,” where “X” can be any one of a number of characteristics such as assembly, manufacturability, reliability, and serviceability. In making such a design, numerous desired characteristics of the product must be considered, including ultimate use, properties, costs, and appearance. Design for environment requires that the designs of the product, the process by which it is made, and the facilities involved in making it conform to appropriate environmental goals and limitations imposed by the need to maintain environmental quality. It must also consider the ultimate fate of the product, particularly whether it can be recycled at the end of its normal life span.

Products, Processes, and Facilities

In discussing design for environment, the distinctions among products, processes, and facilities must be kept in clear perspective. **Products**—automobile tires, laundry detergents, and refrigerators—are items sold to consumers. **Processes** are the means of producing products and services. For example, tires are made by a process in which hydrocarbon monomers are polymerized to produce rubber molded in the shape of a tire with a carcass reinforced by synthetic fibers and steel wires. A **facility** is where processes are carried out to produce or deliver products or services. In cases where services are regarded as products, the distinction between products and processes becomes blurred. For example, a lawn-care service delivers products in the forms of fertilizers, pesticides, and grass seeds, but also delivers pure services including mowing, edging, and sod aeration.

Although *products* tend to get the most public attention in consideration of environmental matters, *processes* often have more environmental impact. Successful process designs tend to stay in service for many years and to be used to make a wide range of products. While the product of a process may have minimal environmental impact, the process by which the product is made may have marked environmental effects. An example is the manufacture of paper. The environmental impact of paper as a product, even when improperly discarded, is not terribly great, whereas the process by which it is made involves harvesting wood from forests, high use of water, potential emission of a wide range of air pollutants, and other factors with profound environmental implications.

Processes develop symbiotic relationships when one provides a product or service utilized in another. An example of such a relationship is that between steel making and the process for the production of oxygen required in the basic oxygen process by which carbon and silicon impurities are oxidized from molten iron to produce steel. The long lifetimes and widespread applicability of popular processes make their design for environment of utmost importance.

The nature of a properly functioning system of industrial ecology is such that processes are even more interwoven than would otherwise be the case, because byproducts from some processes are used by other processes. Therefore, the processes employed in such a system and the interrelationships and interpendencies among them are particularly important. A major change in one process may have a "domino effect" on the others.

Key Factors in Design for Environment

Two key choices that must be made in design for environment are those involvingmaterials and energy. The choices of materials in an automobile illustrate some of the possible tradeoffs. Steel as a component of automobile bodies requires relatively large amounts of energy and involves significant environmental disruption in the mining and processing of iron ore. Steel is a relatively heavy material, so more energy is involved in moving automobiles made of steel. However, steel is durable, is easy to recycle, and is produced initially from abundant sources of iron ore. Aluminum is much lighter than steel and quite durable. It has an excellent percentage of recycling. Good primary sources of aluminum, bauxite ores, are not as abundant as iron ores, and large amounts of energy are required in the primary production of aluminum. Plastics are another source of automotive components. The light weight of plastic reduces automotive fuel consumption, plastics with desired properties are readily made, and molding and shaping plastic parts is a straightforward process. However, plastic automobile components have a low rate of recycling.

Three related characteristics of a product that should be considered in design for environment are durability, repairability, and recyclability. **Durability** simply refers to how well the product lasts and resists breakdown in normal use. Some products are notable for their durability; ancient two-cylinder John Deere farm tractors from the 1930s and 1940s are legendary in farming circles for their durability, enhanced by the affection engendered in their owners, who tend to preserve them. **Repairability** is a measure of how easy and inexpensive it is to repair a product. A product that can be repaired is less likely to be discarded when it ceases to function for some reason. **Recyclability** refers to the degree and ease with which a product or components of it can be recycled. An important aspect of recyclability is the ease with which a product can be disassembled into constituents consisting of a single material that can be recycled. It also considers whether the components are made of materials that can be recycled.

Hazardous Materials in Design for Environment

A key consideration in the practice of design for environment is the reduction of the dispersal of hazardous materials and pollutants. This can entail the reduction or elimination of hazardous materials in manufacture, an example of which was the replacement of stratospheric ozone-depleting chlorofluorocarbons (CFCs) in foam blowing of plastics. If appropriate substitutes can be found, somewhat toxic and persistent chlorinated solvents should not be used in manufacturing applications such as parts washing. The use of hazardous materials in the product—such as batteries containing toxic cadmium, mercury, and lead—should be eliminated or minimized. Pigments containing heavy metal cadmium or lead should not be used if there are any possible substitutes. The substitution of hydrochlorofluorocarbons and hydrofluorocarbons for ozone-depleting CFCs in products (refrigerators and air conditioners) is an example of a major reduction in environmentally damaging materials in products. The elimination of extremely persistent polychlorinated biphenyls (PCBs) from electrical transformers removed a major hazardous waste problem due to the use of a common product (although PCB spills and contamination from the misuse and disassembly of old transformers has remained a persistent problem even up to the present).

19.13 OVERVIEW OF AN INTEGRATED INDUSTRIAL ECOSYSTEM

Figure 19.8 provides an overview of an integrated industrial ecosystem including all the components defined and discussed earlier in this chapter. Such a system can be divided into three separate, somewhat overlapping sectors controlled by thefollowing: (1) the raw materials supply and processing sector, (2) the manufacturing sector, and (3) the consumer sector.

There are several important aspects of a complete industrial ecosystem. One of these is that, as discussed in the preceding section, there are several points at which materials can be recycled in the system. A second aspect is that there are several points at which wastes are produced. The potential for the greatest production of waste lies in the earlier stages of the cycle in which large quantities of materials with essentially no use associated with the raw material, such as ore tailings, may require disposal. In many cases, little if anything of value can be obtained from such wastes and the best thing to do with them is to return them to their source (usually a mine), if possible. Another big source of potential wastes, and often the one that causes the most problems, consists of postconsumer wastes generated when a product's life cycle is finished. With a properly designed industrial ecology cycle, such wastes can be be minimized and, ideally, totally eliminated.

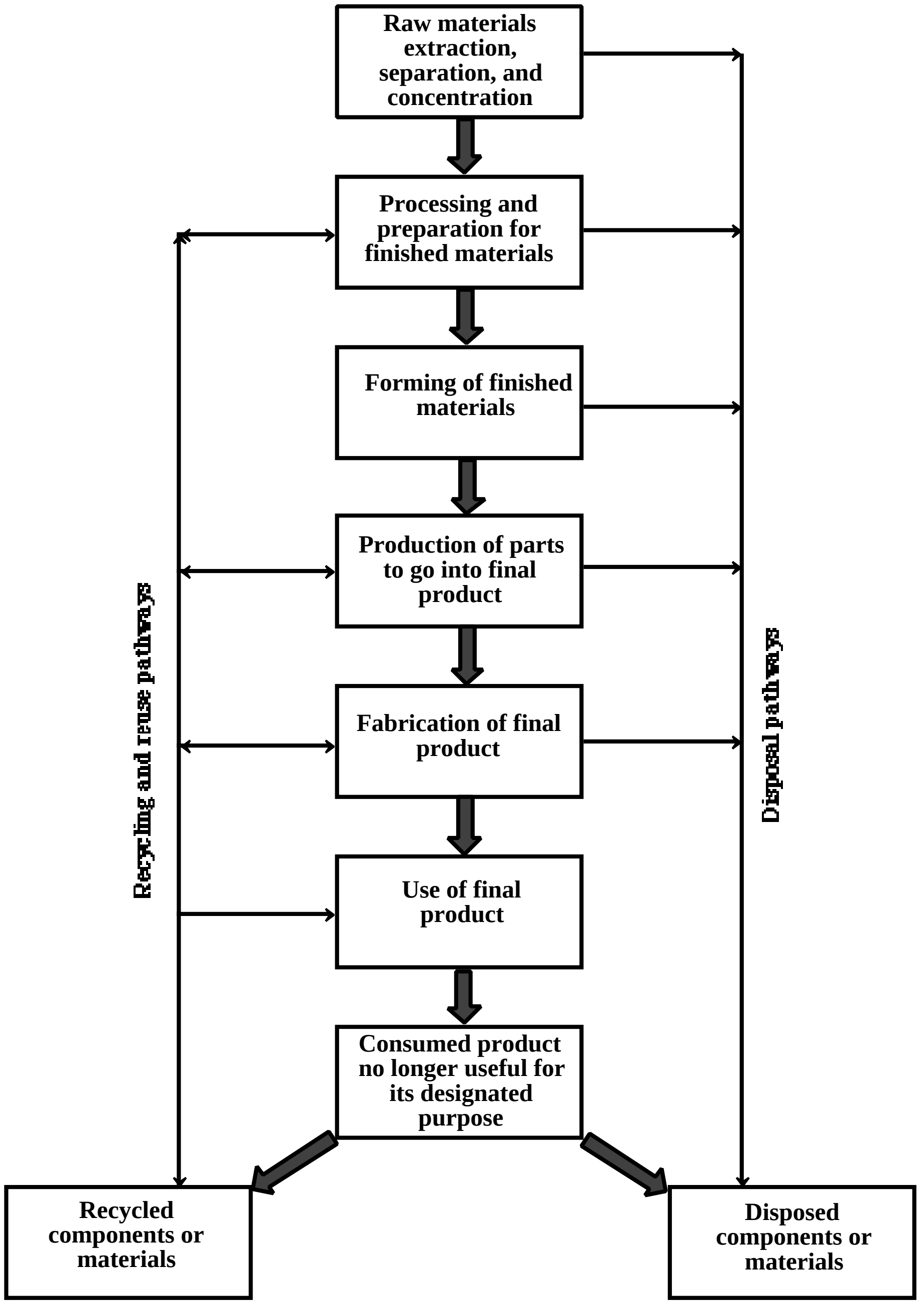

Figure 19.8 Outline of materials flow through a complete industrial ecosystem.

In general, the amount of waste per unit output decreases in going through the industrial ecology cycle from virgin raw material to final consumer product. Also, the amount of energy expended in dealing with waste or in recycling decreases farther into the cycle. For example, waste iron from the milling and forming of automobile parts can be recycled from a manufacturer to the primary producer of iron as scrap steel. To be used, such steel must be remelted and run through the steel manufacturing process again, with a considerable consumption of energy. However, a postconsumer item, such as an engine block, can be refurbished and recycled to the market with relatively less expenditure of energy.

At the present time, the three major enterprises in an industrial ecology cycle, the materials producer, the manufacturer, and the consumer, act largely independently of each other. As raw materials become scarcer, there will be more economic incentives for recycling and integration of the total cycle. Furthermore, there is a need for better, morescientifically based regulatory incentives leading to the practice of industrial ecology.

19.14 THE KALUNDBORG EXAMPLE

The most often cited example of a functional industrial ecosystem is that of Kalundborg, Denmark. The various components of the Kalundborg industrial ecosystem are shown in Figure 19.9. To a degree, the Kalundborg system developed spontaneously, without being specifically planned as an industrial ecosystem. It is based upon two major energy suppliers, the 1,500-megawatt ASNAES coal-fired electrical power plant and the 4–5 million tons/year Statoil petroleum refining complex, each the largest of its kind in Denmark. The electric power plant sells process steam to the oil refinery, from which it receives fuel gas and cooling water. Sulfur removed from the petroleum goes to the Kemira sulfuric acid plant. Byproduct heat from the two energy generators is used for district heating of homes and commercial establishments,as well as to heat greenhouses and a fish-farming operation. Steam from the electrical power plant is used by the $2 billion

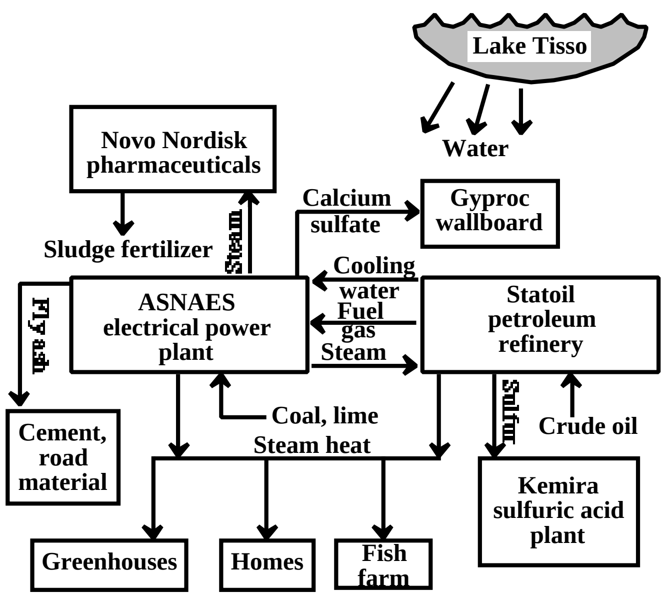

Figure 19.9 Schematic of the industrial ecosystem in Kalundborg, Denmark.

per year Novo Nordisk pharmaceutical plant, a firm that produces industrial enzymes and 40% of the world's supply of insulin. This plant generates a biological sludge that is used by area farms for fertilizer. Calcium sulfate produced as a byproduct of sulfur removal by lime scrubbing from the electrical plant is used by the Gyproc company to make wallboard. The wallboard manufacturer also uses clean-burning gas from the petroleum refinery as fuel. Fly ash generated from coal combustion goes into cement and roadbed fill. Lake Tisso serves as a freshwater source. Other examples ofefficient materials utilization associated with Kalundborg include use of sludge from the plant that treats water and wastes from the fish farm's processing plant for fertilizer, and blending of excess yeast from Novo Nordisk's insulin production as a supplement to swine feed.

The development of the Kalundborg complex occurred over a long period of time, beginning in the 1960s, and provides some guidelines for the way in which an industrial ecosystem can grow naturally. The first of many synergistic (mutually advantageous) arrangements was cogeneration of usable steam along with electricity by the ASNAES electrical power plant. The steam was first sold to the Statoil petroleum refinery; then, as the advantages of large-scale, centralized production of steam became apparent, steam was also provided to homes, greenhouses, the pharmaceutical plant, and the fish farm. The need to produce electricity more cleanly than was possible simply by burning high-sulfur coal resulted in two more synergies. Installation of a lime-scrubbing unit for sulfur removal on the power plant stack resulted in the production of large quantities of calcium sulfate, which found a market in the manufacture of gypsum wallboard. It was also found that a clean-burning gas by-product of the petroleum refining operation could be substituted in part for the coal burned in the power plant, further reducing pollution.

The implementation of the Kalundborg ecosystem occurred largely because of the close personal contact among the managers of the various facilities in a relatively close social and professional network over a long period of time. All the contracts have been based upon sound business fundamentals and have been bilateral. Each company has acted upon its perceived self-interest, and there has been no master plan for the system as a whole. The regulatory agencies have been cooperative, but not coercive in promoting the system. The industries involved in the agreements have fit well, with the needs of one matching the capabilities of the other in each of the bilateral agreements. The physical distances involved have been small and manageable; it is not economically feasible to ship commodities such as steam or fertilizer sludges for long distances.

19.15 SOCIETAL FACTORS AND THE ENVIRONMENTAL ETHIC

The "consumer society" in which people demand more and more goods, energy-consuming services, and other amenities that are in conflict with resource conservation and environmental improvement runs counter to a good workable system of industrial ecology. Much of the modern lifestyle and corporate ethic is based upon persuading usually willing consumers that they need and deserve more things, and that they should adopt lifestyles that are very damaging to the environment. The conventional wisdom is that consumers are unwilling to significantly change their lifestyles and lessen their demands on world resources for the sake of environmental preservation. However, in the few examples in which consumers have been given a chance to exercise good environmental citizenship, there are encouraging examples that they will do so willingly. A prime example of this is the success of paper, glass, and can recycling programs in connection with municipal refuse collection, implemented to extend landfill lifetimes.

Two major requirements for the kind of public ethic that must accompany any universal adoption of systems of industrial ecology are **education** and **opportunity**. Starting at an early age, people need to be educated about the environment and its crucial importance in maintaining the quality of their lives. They need to know about realistic ways, including the principles of industrial ecology, by which their environment can be maintained and improved. The electronic and print media have a very important role to play in educating the public regarding the environment and resources. Given the required knowledge, the majority of people will do the right thing for the environment.

People also need good opportunities for recycling and for general environmental improvement. It is often said that people will not commute by public transit, but of course they will not do so if public transit is not available, or if it is shabby, unreliable, and even dangerous. They will not recycle cans, paper, glass, and other consumer commodities if convenient, well-maintained collection sites are not accessible to them. There are encouraging examples, including some from the United States, that opportunities to contribute to environmental protection and resource conservation will be met with a positive response from the public.

CHAPTER SUMMARY

The chapter summary below is presented in a programmed format to review the main points covered in this chapter. It is used most effectively by filling in the blanks, referring back to the chapter as necessary. The correct answers are given at the end of the summary.

Industrial ecology is defined as [1]____
____
____
____
____.
The ways in which an industrial system handles materials and energy, extracting needed materials from sources such as ores, using energy to assemble materials in desired ways, and disassembling materials and components defines [2]_____________
__________________. A number of industrial enterprises acting synergistically, each utilizing products and potential wastes from other members of the system constitutes [3]_________________________. Industrial development that can be sustained without environmental damage and to the benefit of all people defines [4]_____
_____________________________. The benefits of a successfully operating industrial ecosystem include [5]____
____
____

____.
[6]______________________________ occurs when firms utilize each other's residual materials, thus forming the basis of relationships between firms in a functional industrial ecosystem. The five major components of an industrial ecosystem are [7]__

____
____
____
____.
The process that virgin materials entering an industrial system are subjected to starts with [8]_______________, followed by [9]________________, additional [10]______ _____________ steps, and finally additional [11]______________________________ steps leading to the finished materials. Two different recycling streams in the materials processing and manufacturing sector are [12]_________________________ ____. Industrial metabolism as it is now practiced has a vexing tendency to [13]__________________________________ ____________________ materials to an extent that they are no longer useful but are still harmful to the environment. A comparison of the metabolisms of natural ecosystems with that of industrial systems as they are commonly encountered shows that the basic unit of a natural ecosystem is [14]_________________ whereas that of an industrial ecosystem is [15]___________________, recycling in a natural ecosystem is essentially [16]____________ whereas that in an industrial ecosystem is often [17]_____ _________, and the ultimate major function of an organism is [18]________________, whereas that of an industrial system is [19]____________________________________ ___________. At the least efficient level of materials utilization in industrial systems, raw materials are viewed as being [20]_____________________ and no consideration is given to limiting [21]_____________ whereas at the most efficient level materials are [22] to the maximum extent possible and there are no [23]________________. In considering the effects of major anthrospheric activities on other environmental spheres, the greatest potential effect of fossil fuel combustion on the atmosphere is [24] the greatest effects of indus-trial manufacturing and processing on the geosphere results from the effects of the [25]_____________________ industries, the geosphere is affected by crop production because of loss of [26]_______________________ through the action of wind and water [27]____________________, and a major effect on the biosphere of livestock production is [28]_________________________________. Three key attributes of a successful industrial ecosystem are [29] ___________________________________. The four major ways in which material consumption can be reduced are [30]____ _________________________. When a natural or industrial ecosystem is such that if one part of the system is perturbed, there are others that can take its place the system is said to be [31]__________________. Product stewardship refers to [32]______

____.
The greater usability and lower energy requirements for recycling products higher in the order of material flow are called [33]__________________________. Consideration of process/product design in the management of materials, including the ultimate fates of materials when they are discarded in an industrial operation is referred to as [34] . In doing such an assessment [35]____
______________________ provides qualitative and quantitative information regarding

consumption of material and energy resources (at the beginning of the cycle) and releases to the anthrosphere, hydrosphere, geosphere, and atmosphere (during or at the end of the cycle), [36]_________________ provides information about the kind and degree of environmental impacts resulting from a complete life cycle of a product or activity, and an improvement analysis is done to [37]_________
____.
In doing a life-cycle assessment scoping is done to determine [38]________________
____.
Products such as laundry detergents, windshield washer fluids, and fertilizers that are impossible to reclaim after they are used are referred to as [39]_______________
________________. They should meet the three "environmental friendly" criteria of being [40]____.
Recyclables is a term used here to describe materials that are not [41]_________ but are also not [42]_________________. Recyclables in an automobile include [43]_______
______________________. [44]_______________________________________ is the term given to the approach of designing and engineering products, processes, and facilities in a manner that minimizes their adverse environmental impacts and, where possible, maximizes their beneficial environmental effects. In discussing design for environment, it is important to distinguish among the three categories of [45]
. Three related characteristics of a product that should be considered in design for environment are [46]____. The most often cited example of a functional industrial ecosystem is that in [47]
. It is based upon two major [48]____________________. Two major requirements for the kind of public ethic that must accompany any universal adoption of systems of industrial ecology are [49]__________________________________.

Answers to Chapter Summary

1. an approach based upon systems engineering and ecological principles that integrates the production and consumption aspects of the design, production, use, and termination (decommissioning) of products and services in a manner that minimizes environmental impact while optimizing utilization of resources, energy, and capital
2. industrial metabolism
3. an industrial ecosystem
4. sustainable development
5. reduced pollution, high energy efficiency, reduced consumption of virgin materials, maximization of materials recycle, reduction of amounts of wastes, and increased market value of products relative to material and energy consumption.
6. Industrial symbiosis
7. (1) a primary materials producer, (2) a source or sources of energy, (3) a materials processing and manufacturing sector, (4) a waste processing sector, and (5) a consumer sector.
8. extraction
9. concentration
10. refining
11. processing and preparation

12. process recycle streams external and recycle streams
13. dilute, degrade, and disperse
14. an organism
15. a firm
16. complete
17. very low
18. reproduction
19. production of goods or services
20. unlimited
21. wastes
22. recycled
23. wastes
24. greenhouse warming
25. extractive
26. topsoil
27. erosion
28. loss of species diversity
29. energy, materials, and diversity
30. dematerialization, substitution, recycling, and waste mining
31. robust
32. retention of custody of products to control their fates
33. embedded utility
34. life-cycle assessment
35. inventory analysis
36. impact analysis
37. determine measures that can be taken to reduce impacts on the environment or resources
38. the boundaries of time, space, materials, processes, and products to be considered
39. consumable products
40. degradable, nonbioaccumulative, and nontoxic
41. used up
42. durable items
43. motor oil and antifreeze
44. Design for environment
45. products, processes, and facilities
46. durability, repairability, and recyclability
47. Kalundborg, Denmark
48. energy suppliers
49. education and opportunity

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QUESTIONS AND PROBLEMS

1. In biological ecosystems a process called mineralization occurs as defined in this book. Name and describe a process analogous to mineralization that occurs in an industrial ecosystem.
2. How are the terms industrial metabolism, industrial ecosystem, and sustainable development related to industrial ecology?
3. How is industrial symbiosis related to industrial ecology?
4. Justify or refute the statement that in an operational industrial ecosystem only energy is consumed.
5. In what sense is the consumer sector the most difficult part of an industrial ecosystem?

6. In what sense might a "moon station" or a colony on Mars advance the practice of industrial ecology?
7. In what sense do modern solid state electronic devices illustrate both dematerialization and material substitution?
8. As applied to material resources, what is the distinction between dematerialization and material substitution? Use the automobile as an example.
9. How does "design for recycling" (DFR) relate to embedded utility?
10. Distinguish among consumable, durable (service), and recyclable products.
11. List some of the "environmentally friendly" criteria met by soap as a consumable commodity.
12. What are the enterprises that serve to underpin the Kalundborg industrial ecosystem? How might they compare with the basic enterprises of an industrial ecosystem consisting of rural counties in the state of Iowa?