

Chapter 16

Industrial Ecology

16.1 Introduction

Industrial ecology is an approach to sustainable development that combines the sciences of environment, ecology, and engineering technology. The word *industrial* indicates that the approach focuses on manufacturing processes of a complex of products, which eventually can be interrelated. The significance of the term *ecology* is twofold: first, that man-designed industrial systems can mimic natural ecosystems (bio-mimetics of natural cycles); second, that minimization of the environmental impact of the designed process is an important goal.

The industrial ecology approach was proposed in a paper by Frosch and Gallopoulos (1989) that raised the question, Can our industrial system behave like an ecosystem? That is, can the wastes (or outputs) from one industrial process become the inputs for another industrial process? The answer is yes. Thus, in principle, an industrial park can be designed so that it minimizes the use of primary resources and of overall wastes while recycling or reusing the intermediate materials. One can say that industrial ecology is a method of designing industrial systems so that they produce less damage to the environment. The approach seeks a reasonable balance between industrial profit and environmental stewardship and thereby can contribute to sustainable development.

White (1994) defines industrial ecology as “the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources.” Since industrial ecology aims to design and analyze fluxes of energy and matter, industrial ecology methods can beneficially incorporate exergy to provide more powerful tools. Exergy analysis pinpoints significant losses in the processes, or nonrecoverable losses of the exergy associated with primary energy sources. An attempt to develop exergy analysis from an industrial ecology perspective as conducted by Dincer and Rosen (2007) will be discussed later in this chapter.

One typical example is application of the industrial ecology concept to the design of industrial parks. Thermodynamic and economic analyses must be complemented in this case with ecology and waste management studies, societal impact

analysis, and creating the legal and economic framework that enables companies to act for the benefit of the overall system. In brief, industrial ecology is concerned with shifting industrial processes from linear (open loop) systems, in which resource and capital investments move through the system to become waste, to closed loop systems, in which wastes become the inputs for new processes.

According to the above conception, modern industrial technologies should be designed like ecosystems where (1) input mass and energy flows are minimized and (2) energy supply is provided by renewable energy sources. Minimization of fossil fuel energy consumption in industrial processes implies eliminating output waste energy flows or the emission of wastes that are in equilibrium with the conditions (pressure, temperature, composition) of the environment. Figure 16.1 shows three situations illustrating a gradual minimization of input and output material and energy streams. Case 1 (the reference case) entails three technologies or manufacturing processes that evolve within the same industrial park. One step toward implementing industrial ecology is shown in case 2 (reduced waste) where the waste from technology 1 is taken as input to technology 2; thus the inputs and outputs (wastes) from the overall process are reduced.

In the third case, all three processes are coupled in a loop, and there is no material input or waste output. The only requirement for the process to run is the energy. In a completely sustainable scenario, the input energy should be in the form of renewable energy.

16.2 Relevant Natural and Industrial Cycles

Industrial ecology is concerned with the design of industrial systems in an ecological manner. All fluxes of materials and energy must be inventoried and integrated with the biogeochemical cycles of nature. One of the main goals of industrial ecology design is accounting for the natural cycles of substances. Moreover, the natural cycles are seen as an inspiration for designing material cycles in industry. There are five biogeochemical cycles of nature—water, nitrogen, carbon, sulfur, and phosphorus—which we briefly review here.

The water (or hydrologic) cycle is driven by solar energy as water evaporates or ice sublimates and the generated vapor rises in the atmosphere where it eventually condenses and generates rain. There are several mechanisms involved in the hydrologic cycle: evaporation, transpiration, sublimation, cloud formation, precipitation, canopy interception, infiltration, runoff, subsurface flow, and advection. The residence time of water in the atmosphere is 9 days, in rivers up to 6 months, and in the oceans up to 3,000 years.

It is obvious that the impact of human activities on the amount of water circulated on the earth is not considerable. However, industrialization has drastically changed in some cases the local water balances (e.g., installation of large water dams for hydroelectricity, expelling into the atmosphere water vapor from combustion exhausts). Moreover, the global warming effect, which is a

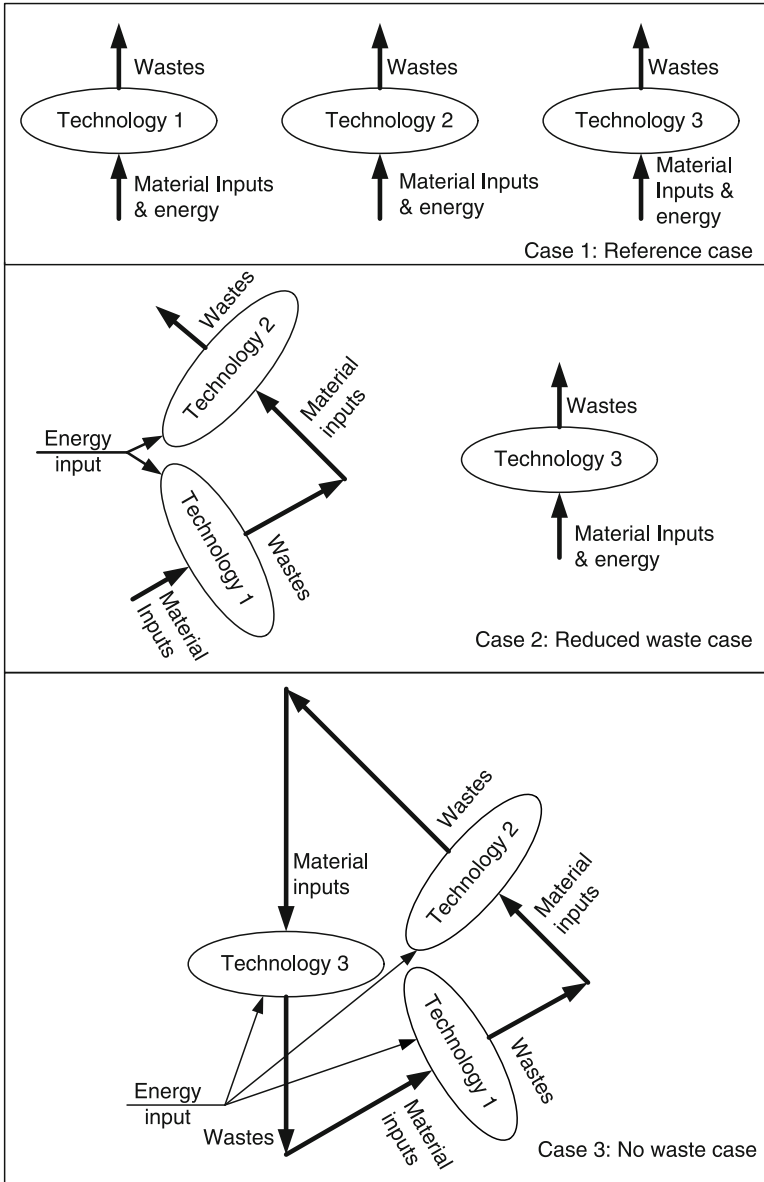


Fig. 16.1 Illustrating the industrial ecology concept

consequence of the industrial activity of humans, accelerates the hydrologic cycle. The water cycle is relevant in industrial ecology because of its indirect effect of circulating other chemicals through the atmosphere, waters, and soil. For example, the flow of water beneath the earth is one of the most important means of transportation of other chemicals. Phosphorus is transported from land to lakes

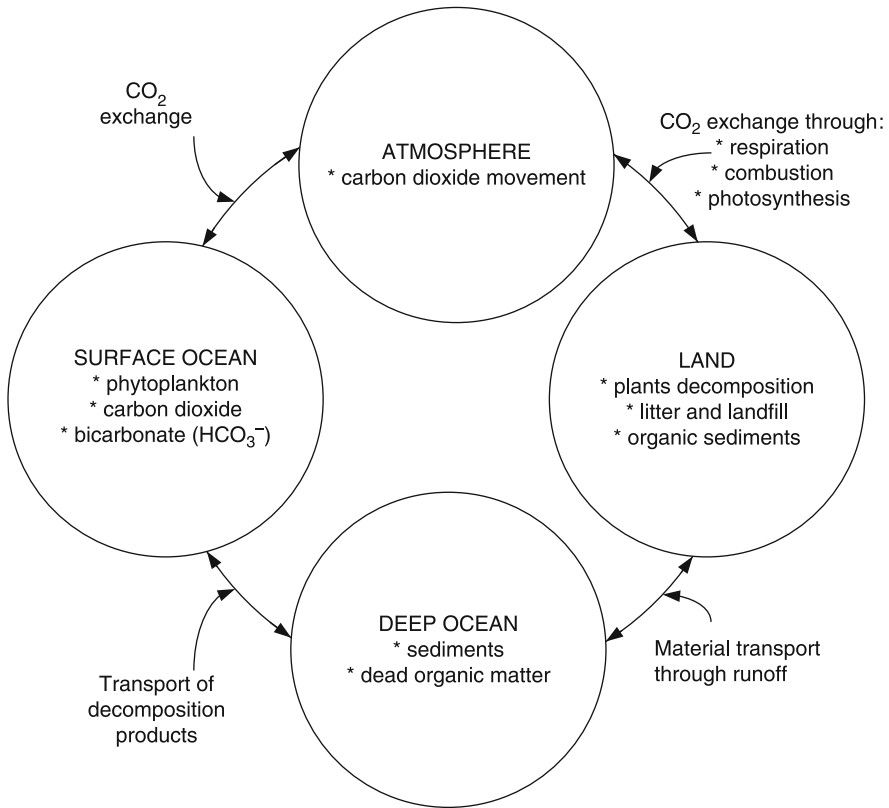


Fig. 16.2 The carbon cycle in nature

or oceans mainly through runoff. After erosion and dissolving processes, salt is transported from the land to the seas. Underground water and runoff are important in circulating nitrogen from soil to water bodies.

The carbon cycle is next in importance after the hydrologic cycle. The carbon itself can be transported by water in the form of eroded solid materials or various kind of particulate matter (including that originating from human activity). Figure 16.2 illustrates the carbon cycle in nature. The carbon dioxide emissions in the atmosphere increased by $\sim 6\%$ per annum since 1900 due to fossil fuel combustion in the industrial era. Presently, about 8 Gt are emitted each year. However, the contribution of the fossil fuel combustion process is a small percent of the total carbon circulation. The soil contains about two times more carbon than does the atmosphere. The ocean assimilates ~ 50 Gt annually, from which 90% is returned to the superficial water layer, where it is partially assimilated by phytoplankton and partially released back to the atmosphere. In the oceans, 95% of the sequestered carbon is present in the form of bicarbonate. The anthropogenic CO_2 released in the atmosphere in the industrial era produced an increase of the troposphere temperature

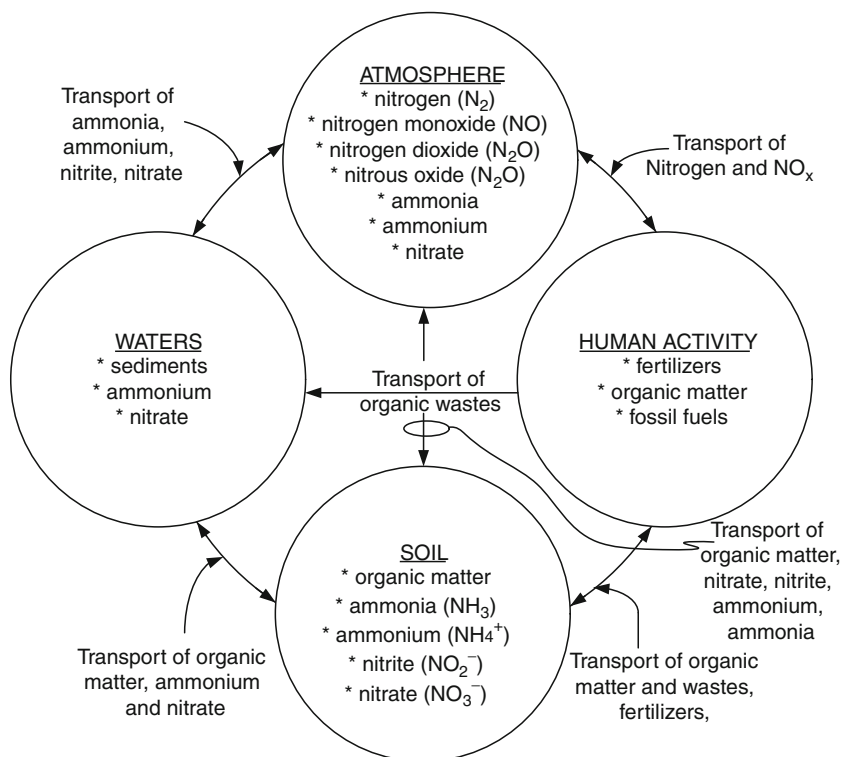


Fig. 16.3 Nitrogen cycle in nature and human activity

by 2° to $3^\circ C$ (on average). This increase raises major concern due to the rapid global warming that intensifies the hydrologic cycle. Thus any industrial process must be designed or retrofitted for minimum CO_2 release into the atmosphere.

The global nitrogen cycle is illustrated in Fig. 16.3, along with the major interaction of this natural cycle with human activity. The principal forms in which nitrogen is present in the global ecosystem are the nitrogen molecule with three (strong) covalent bonds (N_2), ammonia (NH_3), ammonium (NH_4^+), nitrous oxide (N_2O), nitrate (NO_3^-), and nitrite (NO_2^-). The earth's reservoir of nitrogen is the atmosphere, which comprises a volumetric percentage of 78.1% nitrogen.

Nitrogen is an element present in all life systems as a constituent of amino and nucleic acids, proteins, chlorophyll, and animal excretions. However, nitrogen cannot be used in its molecular form by life systems because its molecule is very stable: it has three strong covalent bonds. The activation energy for nitrogen cracking, which is equivalent to the energy needed for breaking the triple covalent bond of the nitrogen molecule ($N \equiv N \rightarrow 2N^{3+} + 6e^-$), namely 460 kJ/mol, appears to be insurmountable, so that this energy is higher than the formation energy of other stable molecules such as carbon dioxide (-393.5 kJ/mol) or water (-241.82 kJ/mol).

Microbes and bacteria have the ability to fix nitrogen (i.e., to convert the stable molecule of atmospheric nitrogen into reactive compounds) thanks to nitrogenase, which is the most complex enzyme capable of breaking the nitrogen molecule and generating ammonia. Therefore, nitrogenase performs a crucial step in the global nitrogen cycle, namely that of transforming nitrogen captured from the atmosphere by living organisms, through specific respiration mechanisms, and converting it into ammonia. Further, ammonia is easily manipulated by biological cells by converting it into ammonium and other compounds such as nitrate and nitrite, and synthesizing more complex chemicals such as urea. Other natural ways to fix nitrogen is through lightning; when lightning occurs, the released energy is sufficient to transform amounts of atmospheric N_2 into NO_x , which can be further converted by living species to nitrates, which are more soluble and more easily manipulated compounds. However, lightning is responsible for a minute portion of natural nitrogen fixation compared with the enzymatic process that fixes the overwhelming majority.

The opposite of the nitrogen fixation process is the process of denitrification, which converts nitrites and nitrates into mainly nitrogen molecules and some amounts of NO_x and nitrous oxide (N_2O) that are released back into the atmosphere. Recall that nitrous oxide has a greenhouse effect 200 times stronger than that of CO_2 . Nitrogen is returned into the atmosphere also in the form of ammonia; the NH_3 is stable in the atmosphere and dissolves in water, through which it is redeposited on the soil through rain. According to Tsunogai and Igeuki (1968), the residence time of ammonia in the atmosphere is ~ 30 days, which is much shorter than that of other atmospheric gases.

Humans intervene to a major extent in the natural nitrogen cycle, mainly through the use of artificial fertilizers and the combustion of fossil fuels. Starting in the second half of the twentieth century, production of ammonia through the Haber–Bosch process became economically efficient and expanded rapidly so that in 2008 the global ammonia synthesis surpassed 130 Mt. Through the Haber–Bosch process, the nitrogen molecule is cracked by heating at temperatures over 850 K and then combined with hydrogen by catalysts at elevated pressures. The process uses either natural gas or coal as the primary energy input and materials from which hydrogen is synthesized as a first step. Nitrogen is extracted from the atmosphere through air separation methods. Basically, Haber–Bosch is the artificial path invented by humans to fix the atmospheric nitrogen. All nitrogen fixed through artificial ammonia synthesis is used as fertilizers (80%) or as building blocks for other synthetic chemicals (20%). Another artificial path of nitrogen fixation is combustion processes, which generates NO_x in an annual estimated amount, according to Smil (2002), of ~ 25 Mt nitrogen.

The high pace of artificial nitrogen fixation is not compensated through artificial denitrification. Therefore, the role of the denitrification process (converting the nitrogen reactive compounds into stable atmospheric nitrogen) is left in the hands of nature. Whether natural mechanisms of denitrification can keep pace with artificial fixation is an open question. The industrial ecology approach can play a major role in balancing artificial fixation with natural and artificial denitrification so that the environment is affected minimally by human activity.

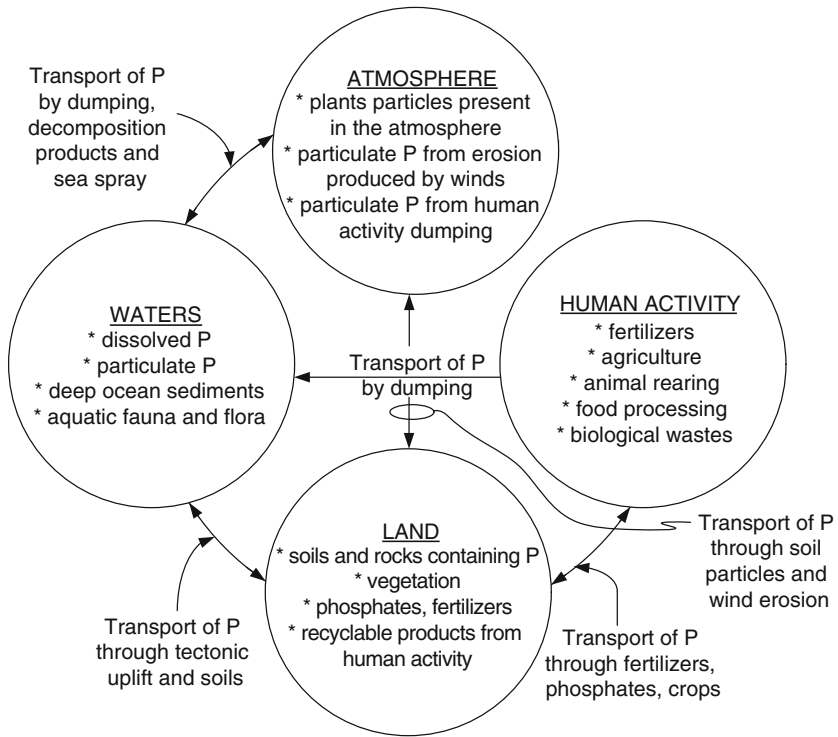


Fig. 16.4 The phosphorus cycle in nature and human activity

The phosphorus (P) cycle in nature is affected by human activity that manipulates phosphorus through fertilizers and biological wastes. With respect to the nitrogen cycle, there is no direct interaction between human activity and the transport of phosphorus in the atmosphere, as seen in Fig. 16.4. The biological wastes, fertilizers, and phosphates resulting from human activity are dumped mainly on land; some of the phosphorus dumping reaches water. In the land, the phosphorus is present in soils, rocks, phosphates (fertilizers), and other products resulting from human (industrial, agricultural, etc.) activity. Tectonic uplift and soils transport phosphorus between soil and water, while winds, through erosion, transport phosphorus from land into the atmosphere. In waters, the phosphorus is present in dissolved or particulate forms, in various sediments from deep oceans, and as a constituent of aquatic fauna and flora.

Figure 16.5 presents the distribution of phosphorus, globally, as a consequence of the natural cycle and of manmade activities. The largest storage of phosphorus is in soils (40 Gt) and the smallest results from weathering of rocks and materials containing P.

Phosphorus is recycled rapidly in the biosphere because life systems are capable of harvesting it in diluted form and concentrating it up to 1,000 times. For example, according to Smil (2002), the marine phytomass processes 1 Gt of phosphorus

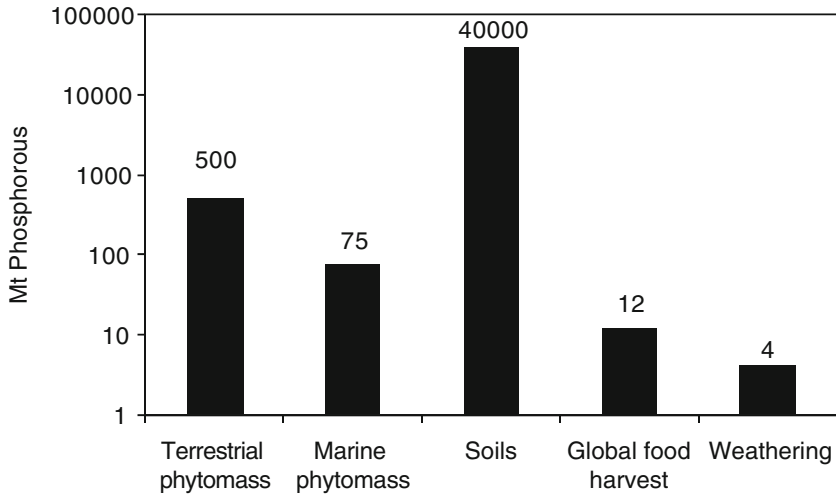


Fig. 16.5 Distribution of phosphorus storage [data from Smil (2002)]

annually and the terrestrial phytomass processes up to 100 Mt/year. Nevertheless, phosphorus is one of the most important elements for life systems, because it is present in adenosine triphosphate (ATP) and in nucleic acids. Phosphorus is present in nature in larger amounts as calcium phosphates. In human activity, phosphorus is present mainly in the form of fertilizers.

Sulfur is also an important element for life systems due to its role in linking amino acids and forming proteins. Sulfur is transported through the ecosystem mainly in the form of the following chemicals: sulfate (SO_4^{2-}), sulfur dioxide (SO_2), hydrogen sulfide (H_2S), dimethyl sulfide ($\text{C}_2\text{H}_6\text{S}$), and carbonyl sulfide (COS).

The residence time of sulfur in the atmosphere, as embedded in various chemicals, is very short (from minutes to a maximum of 3 to 4 days); thus sulfur cannot be transported far. Therefore, the natural cycle of sulfur manifests regionally rather than locally (Fig. 16.6).

The main mechanisms of sulfur transport are by sea spray, volcanic eruptions, airborne dust and precipitations, and biogenic and anthropogenic emissions. In Fig. 16.7 are illustrated the annual rates of various transport mechanisms of sulfur through the ecosystem. The plot is constructed based on data from Smil (2002). The anthropogenic emissions of sulfur (93%) originate from the combustion of fossil fuels, while 7% come from smelting of metallic sulfides (Smil 2002). From Fig. 16.7, it can be deduced that the rate of anthropogenic sulfur emissions represents roughly 23% from all sulfur transport mechanisms occurring in the ecosystems.

Here, we also illustrate some examples of material cycles that occur in industrial activity. It will become evident that industrial cycles present similarly to natural cycles. Both are subjected to the general laws of physics that state, for example, that energy is never destroyed, mass is conserved, and if no nuclear reactions take place,

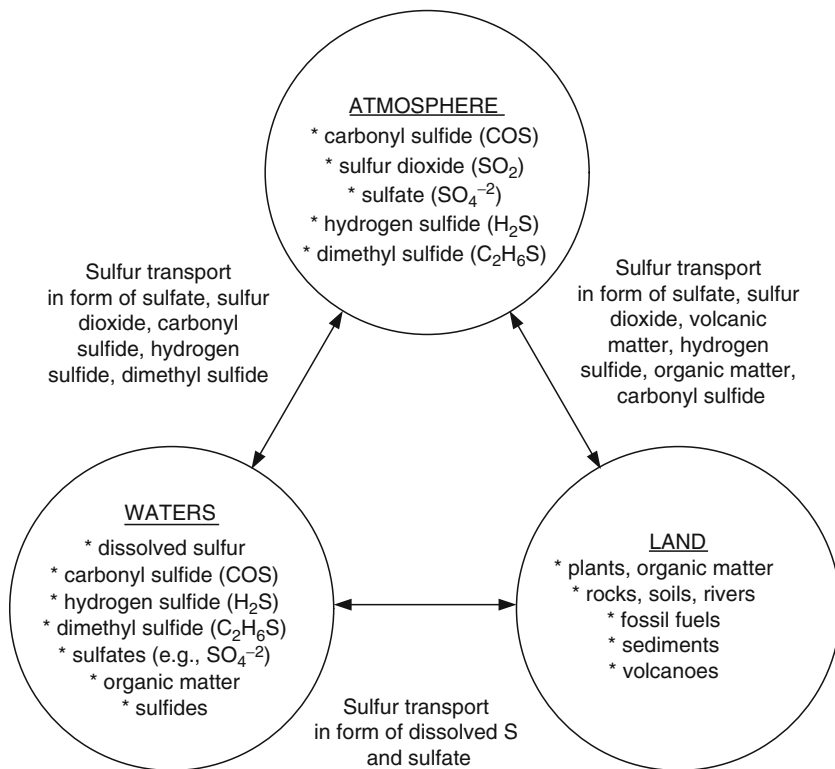


Fig. 16.6 The sulfur cycle in nature

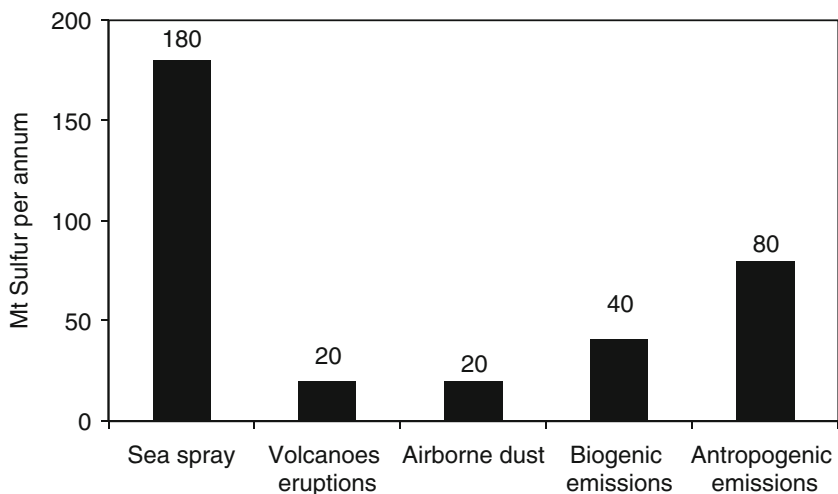


Fig. 16.7 The annual rates of sulfur transport through the ecosystem

the chemical elements are conserved. In the first few examples, the cycle of platinum group materials (PGMs) is illustrated for European countries.

Platinum group metals consist mainly of platinum (Pt), palladium (Pd), and rhodium (Rh) and are found in many industrial materials starting with catalysts, electrical appliances, jewels, dental prostheses, glass-based materials, and others. European countries obtain their primary sources of PGM from four countries: the United States, Canada, Russia, and South Africa. Due to the high values of the PGMs, these metals are highly recycled. The high cost explains the fact that industrial ecology for PGM processing is currently in effect, mainly in the form of material recycling, reprocessing, and reuse. The data from Saurat and Bringezu (2008) have been used to build the European flow diagram of PGM as illustrated in Fig. 16.8. From 100% of extracted PGM (by mass) only 80% arrives in Europe, while the rest is wasted during the preliminary processing in the countries of origin. There are high greenhouse gas (GHG) emissions associated with the extraction and preprocessing of PGMs, amounting, as indicated in Fig. 16.8, to ~60,000% of the extraction.

Europe uses, recycles, and reprocesses the PGMs extensively; thus, ~2,500 t of GHGs are emitted into the atmosphere per ton of metal. There are four major sectors in which PGMs are used in Europe: the auto industry (which consumes 62% of imports to produce catalysts), jewelry manufacturing with 5.3%, industrial catalysts with 4.7%, and manufacturing of electric, electronics, and other products with ~8% of the import. The intense recycling of PGMs in Europe makes possible the reuse of ~16% of the metals by weight of the amount imported.

Similar material cycles exist for regular metals used in industry (e.g., iron-based metals). Figure 16.9 illustrates a generic lifecycle diagram that is valid for any industrial metal. After resource extraction comes primary production and metal use. Then, the old scrap and dumped scrap can be partially recovered, reprocessed, and recycled. Thus, one reduces the wastes and the consumption of primary resources. At the same time, the associated pollution (e.g., GHG emissions) is also reduced. The opportunity to recycle and reprocess metals was extensively used in the past; thus, metal cycles are representative examples of an industrial ecology application. Among metal cycles, much attention is paid to the rare/expensive metal, such as the PGMs discussed above. Another example of rare metal cycles, which illustrate the application of the industrial ecology concept is the tungsten cycle. Tungsten is a strategic metal that is used in construction machinery and equipment, electronic equipment, lamps for electronics and for lighting, and dies. Figure 16.10 illustrates the tungsten cycle in the United States. Being an extremely valuable material, the tungsten cycle includes a thorough waste management system that interacts with production, fabrication, and use phases (see Harper 2008).

Figure 16.11 exemplifies the material flow and recycling of plastic materials for product packaging. Plastic sources from secondary products of fossil fuel refineries are used to make two main substances that are constitutive blocks of packing materials: ethylene and styrene. The first is prime matter for polyethylene production, while the second is used for making expanded polystyrene. Plastic materials are recovered from the products through waste management systems, and then recycled and reused for new packaging. Eventually, unrecoverable plastics are expelled in landfill.

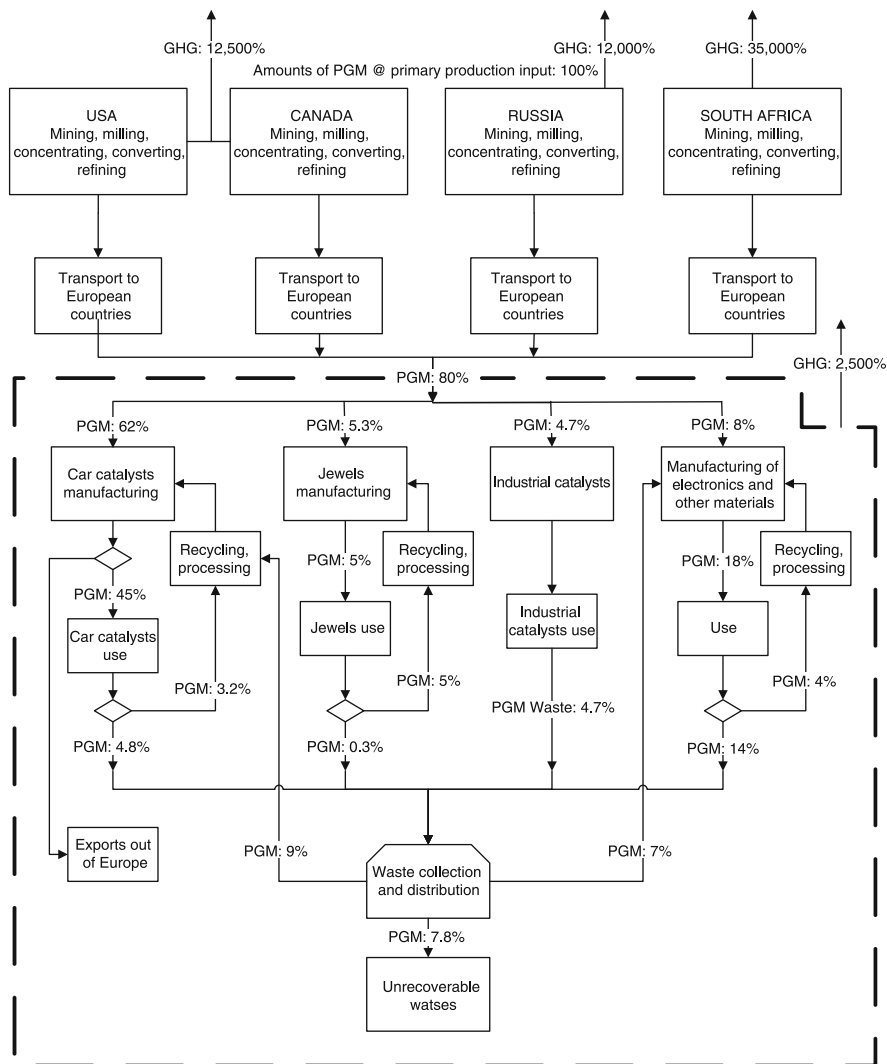


Fig. 16.8 Platinum Group Metals (PGMs) flow in European countries [data from Saurat and Bringezu (2008)]

16.3 Methods of Analysis in Industrial Ecology

There are a number of established analysis methods in industrial ecology that can be applied for a defined system and over a defined period of time. We discuss in this section some of the main analysis methods: material flow analysis (MFA) and the energy and exergy analyses.

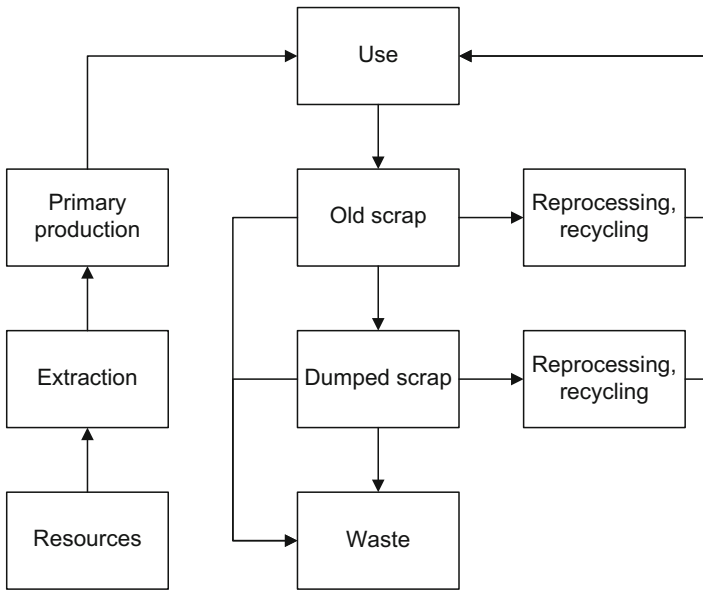


Fig 16.9 Generic diagram for industrial metal life cycle

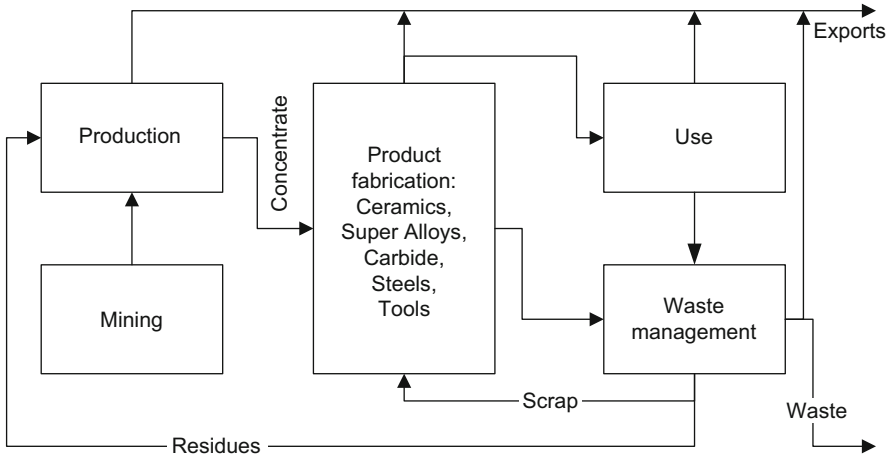


Fig. 16.10 The tungsten cycle in the United States

MFA accounts for inputs and outputs of materials, quantified in physical units, associated with various processes such as resource extraction or harvesting, chemical processing and manufacturing, consumption and use, recycling and reuse, and material disposal. MFA is not supposed to account for energy flows; it is restricted to substance flows. The substances can be categorized in various ways, such as primary resources, intermediate materials and emissions, input materials, products,

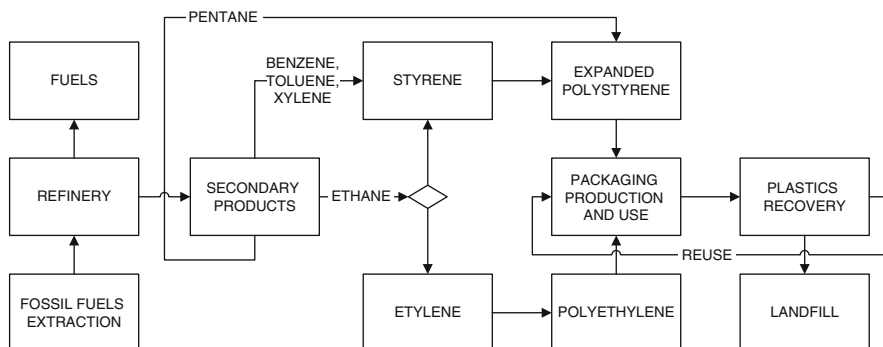


Fig. 16.11 Plastic material flow and recycling for product packaging

and polluting emissions. The methodological principle used for MFA is mass balancing.

When studying the environmental impact, two kinds of MFA are possible, as reported by Bringezu and Moriguchi (2002):

- Analysis within certain companies, sectors of activity, or geopolitical regions of the environmental impact per unit of flow of substances, materials, or products
- Analysis for various substances, materials, or products of the environmental concern related to the throughput of companies, sectors of activity, or geopolitical regions

The results of MFA are of major importance for many subsequent analyses such as energy, economic, or environmental ones. For example, the study of the flow of carbon within an industrial system is important because it is related to GHG emissions. Moreover, the MFA is the basis for defining and deriving various kinds of indicators that quantify the environmental impact or other impacts.

The following steps are recommended for performing an MFA in a systematic manner:

- Defining the system and its spatial–temporal boundaries
- Identifying and categorizing the flows of materials
- Analyzing through mass balance and stoichiometric calculations
- Defining and determining of environmental and other impact coefficients per unit of flow
- Evaluating the results

Another analysis method equivalent to MFA is known as physical input–output accounting. Basically through this method one accounts for all physical flows between the economy and the environment and for all involved material flows. In this method of analysis the processes under study are represented through the associated material inputs and outputs. Further details on this method can be found in Strassert (2002).

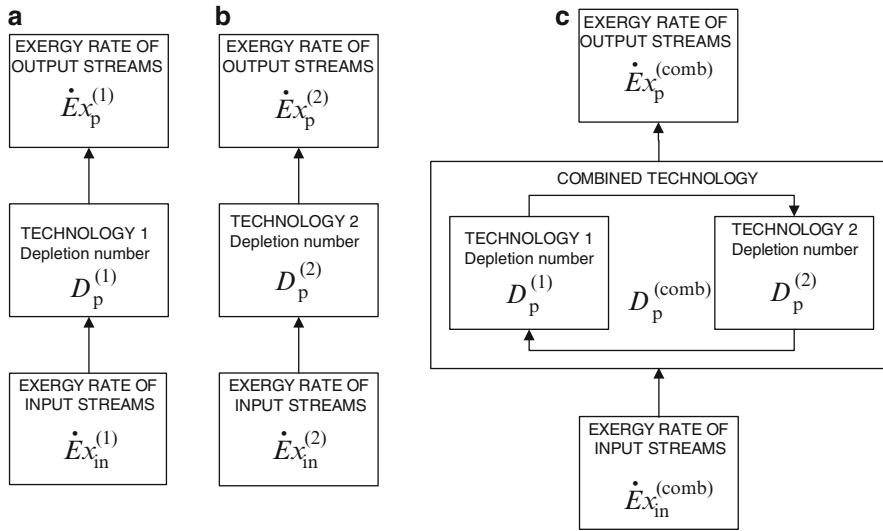


Fig. 16.12 Depletion number of separate and combined technologies

Energy and exergy analyses are thermodynamic methods discussed in Chapter 1 that in principle can be applied to any system. Energy balance accounts for any involved energy flow associated with streams of matter and those associated with any form of energy transport, such as heat, mechanical work, electricity, and fuel.

Exergy as a method of analysis in industrial ecology is useful because it accounts for waste exergy emissions and exergy destructions. Reducing entropy generation leads to a decline in exergy destruction (losses) $\dot{E}x_D$ due to reducing the irreversibility of the processes constituting an industrial system. The exergy efficiency of any process or system generally can be written as

$$\psi = 1 - D_p, \quad (16.1)$$

where D_p is the *depletion number* introduced in Chapter 5 and defined according to Dincer and Rosen (2007) by

$$D_p = \frac{\dot{E}x_D}{\dot{E}x_{in}}, \quad (16.2)$$

where $\dot{E}x_D$ represents the exergy destruction rate and $\dot{E}x_{in}$ the total exergy consumption by the system.

Assume that the analyzed system is from the domain of industrial ecology, that is, it comprises a number of combined technologies and industrial fluxes that operate as a whole. In this case, the exergy efficiency of the integrated system can be evaluated on the basis of the depletion number of each independent component. In an abstract manner, the exergy efficiency of industrial ecology systems is illustrated in Fig. 16.12.

For combined technologies, the depletion number $D_p^{(\text{comb})}$ is lower than for separate technologies $D_p^{(\text{sep})}$, which is expressed as

$$D_p^{(\text{comb})} = \frac{\dot{E}x_{p1}^{\text{comb}}}{\dot{E}x_{p1}^{\text{comb}} + \dot{E}x_{p2}^{\text{comb}}} D_p^{(1)} + \frac{\dot{E}x_{p2}^{\text{comb}}}{\dot{E}x_{p1}^{\text{comb}} + \dot{E}x_{p2}^{\text{comb}}} D_p^{(2)}, \quad (16.3)$$

where $\dot{E}x_{p1}^{\text{comb}}$ and $\dot{E}x_{p2}^{\text{comb}}$ are the rates of output exergy flows for products 1 and 2, respectively.

The application of exergy methods to industrial ecology analysis can be done by calculating the exergy flows of every stream of matter and energy and associating depletion numbers with every independent technology or process. Further, the depletion number of the separate and combined technologies is calculated and compared in order to quantify the benefit of technology integration from both an energetic and ecologic point of view.

16.4 Case Study

Here is an example of integration from energy technology—a system combining power generation and hydrogen production technologies. The system comprises the following technologies: gas turbine, solid oxide fuel cell (SOFC), membrane reactor (MR), and hydrogen generator. It is taken from Dincer and Rosen (2007). Both SOFCs and MRs utilize high-temperature oxygen ion-conductive membranes that permit the separation of oxygen from air. The membranes are applicable as electrolytes in SOFCs. In the case presented here, the chemical exergy of methane fuel is transformed into electrical work through an intermediate stage involving its conversion to hydrogen and carbon monoxide and electrochemical oxidation with oxygen. In a membrane reactor, the membrane conducts both oxygen ions and electrons in opposite directions; such membranes are consequently often called mixed conducting membranes. In this case study the electrical work is not generated, but oxygen is separated from air, and fuel combustion proceeds in an atmosphere of oxygen, which improves the quality/efficiency of combustion.

Several advanced materials must be included in the discussed technologies:

- Ceramic materials including zirconium oxides for membranes that operate at over 500 K
- Noble metal catalysis for electrodes resistant to high temperatures of over 1,000 K
- Catalysts for generation of hydrogen from methane through a reforming process directly at the surface of the electrodes

The process diagram is shown in Fig. 16.13 and operates as follows. The initial stream of natural gas, after heating in device 14 (in order to achieve, after compression, the temperature of combustion products) and compression in device 15, is

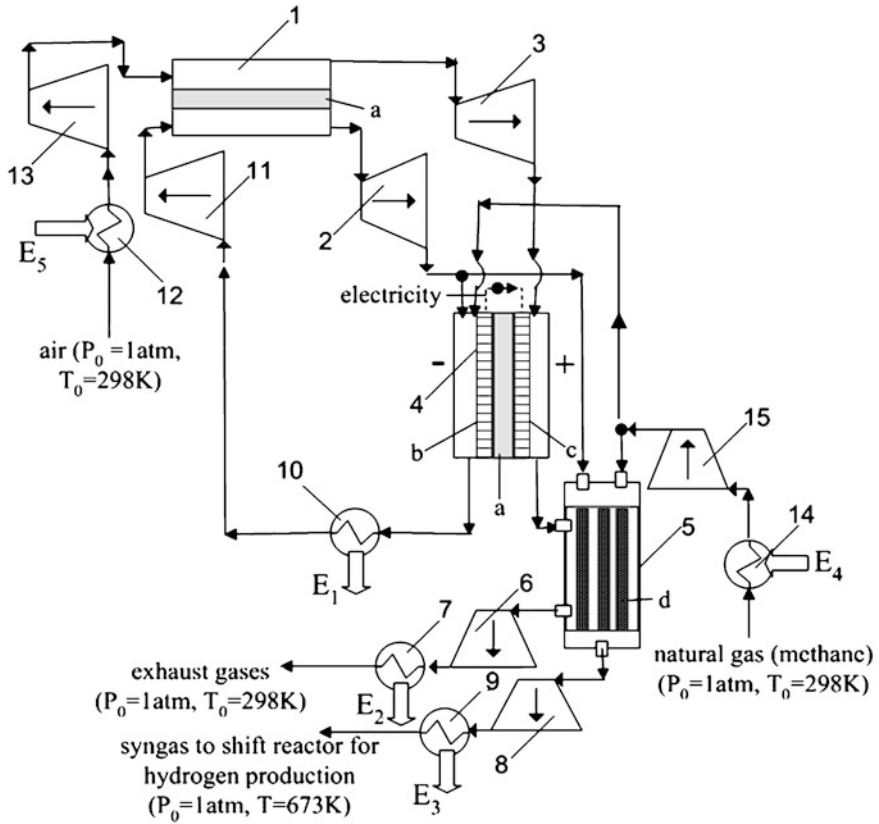


Fig. 16.13 Example of combining hydrogen and power generation technologies [modified from Dincer and Rosen (2007)]: 1, MR; 2, 3, 6, 8, turbines; 11, 13, 15, compressors; 4, SOFC; 5, methane converter; 7, 9, 10, 12, 14, heat exchangers; (a) oxygen conductive membranes; (b, c) anode and cathode of SOFC stack; (d) reactor

divided into two flows. The first is mixed with combustion products (carbon dioxide and steam) and directed to the anodes of the SOFC stack (device 4), where two processes occur simultaneously: conversion of methane into a mixture of carbon monoxide and hydrogen on the surface of the anodes, and electrochemical oxidation of the resultant mixture with oxygen. The oxygen reduction is accompanied by electricity generation in the SOFCs. The gaseous mixture from the anodes (conversion and combustion products) is cooled in a heat exchanger (device 10), compressed in device 11, and directed to the MR (device 1), where the remainder of the conversion products combust in oxygen, and then expand in a turbine (device 2).

The combustion products are then divided into two flows. The first is mixed with the initial flow of methane and directed to the SOFC stack, while the other is mixed with the second flow of methane and enters the catalytic methane converter (device 5). After methane conversion to hydrogen and carbon monoxide in device 5, the gaseous

mixture is expanded in a turbine (device 8), cooled in a heat exchanger (device 9), and directed to the shift reactor, where the remainder of the carbon monoxide and steam is converted to hydrogen.

Air is heated in device 12, compressed in device 13, and directed to the MR (device 1), where some quantity of oxygen is transferred through the oxygen ion-conductive membrane and combusted with fuel. The air heating in device 12 is required in order to achieve, after compression, the temperature of the fuel flow, which is directed, like air, to the MR. The temperature of air reaches its maximum at the MR (device 1) outlet, at which point it is expanded in the turbine (device 3) and directed to the cathodes of the SOFCs (device 4). In the SOFCs, the oxygen concentration in the air decreases, and the air is heated and enters the space between pipes in the catalytic converter (device 5). In device 5, heat is transferred from the air to the reaction mixture in the pipes. The mixture is then expanded in the turbine (device 6) and cooled in the heat exchanger (device 7).

The power generation design combines a traditional gas turbine cycle—which consists of compressors (devices 11 and 13), a combustion chamber (which is represented by the MR, device 1), and turbines (devices 2 and 3)—with the SOFC stack (device 4) and the methane converter (device 5). Heat exchangers are conditionally divided into the heat releasing (devices 7, 9, and 10) and heat receiving (devices 12 and 14) types. Mechanical work is produced in the turbines and consumed in the compressors. The work is transformed into electrical energy, which is also directly generated in the SOFC stack. The endothermic process of methane conversion to hydrogen (via a synthesis gas) in device 5 is implemented into the power generation cycle.

Table 16.1 gives the general parameters used in this analysis, which is done through the exergy method, making a number of assumptions, such as:

- All gases follow the ideal gas law.
- Mechanical friction is negligible throughout the system.
- Thermochemical equilibrium is achieved at the output of the SOFC and the methane converter.
- The combustion process is complete in the membrane reactor.

The exergy balance for the system can be expressed as

$$\Delta\dot{E}x = \dot{E}x_{\text{in}} - \dot{E}x_{\text{out}} = \sum \dot{W}_i + \Delta\dot{E}x_{\text{T}} + \sum \dot{E}x_{\text{D}_i}, \quad (16.4)$$

where $\Delta\dot{E}x$ is the rate of exergy change in the system, $\dot{E}x_{\text{in}}$ is the sum of the exergy rates of the input flows of methane and air, $\dot{E}x_{\text{out}}$ is the sum of the exergy rates of the output flows of conversion products (synthesis gas) directed to a shift converter and exhaust gases, $\sum \dot{W}_i$ is the sum of powers generated in the turbines and in SOFCs, and consumed in the compressors, $\Delta\dot{E}x_{\text{T}}$ is the sum of thermal exergy rates released in heat exchangers 7, 9, and 10 and consumed in 4 and 12, and $\sum \dot{E}x_{\text{D}_i}$ is the sum of the exergy loss rates in the devices of the system. Table 16.2 presents the calculated destroyed exergy for all system components.

Table 16.1 Assumed parameters for the system discussed in Fig. 16.13

Parameter	Value
Isentropic efficiency of turbines η_t	0.9
Isentropic efficiency of compressors η_{cmp}	0.8
Operational circuit voltage of the SOFC stack, V	0.8
Maximum pressure in the gas turbine cycle P_{max} , bar	10
Minimum pressure in the gas turbine cycle P_{min} , bar	1.01325
Maximum temperature in the cycle (at the MR outlet) T_{max} , K	1,500
Temperature of fuel at the inlet of the SOFC stack T_s , K	1,300
Temperature of fuel and air at the outlet of the SOFC stack T_s , K	1,300
Ratio of methane combusted in the power generation cycle to the methane converted	1.0:0.7
Molar ratio of combustion products after MR to the combusted CH_4	6
Ratio of amounts of combustion products directed to SOFC and methane converter	1:1
Standard temperature T_0 , K	300
Standard pressure P_0 , bar	1.01325
Air composition, volume percentage	21% O_2 , 79% N_2

Table 16.2 The destroyed exergy in relevant components of the system from Fig. 16.13

Device	1	2	3	4	5	6	8	11	13	14
Destroyed exergy, kJ/mol	28	3	5	30	17	3	0.3	5	23	1

The data are calculated per mole of combusted methane, which has the standard chemical exergy of $Ex_{\text{CH}_4}^0 = 831.7$ kJ/mol. The system consumes 1.7 mol of methane to generate two useful products: synthesis gas (hydrogen and carbon monoxide) and electricity. Therefore, the depletion number of the combined system is calculated in this case by

$$D_p^{(\text{comb})} = \frac{\sum Ex_{D_i}}{1.7Ex_{\text{CH}_4}^0} = 0.14. \quad (16.5)$$

For 1 mol of methane consumed, the system produces 0.7 mol of syngas. From this proportion and the chemical exergy of hydrogen and carbon monoxide, one can calculate the exergy associated with the syngas, which is $Ex_{\text{SG}}^0 = 656$ kJ/mol. Individual efficiencies of technologies were estimated based on the known performance parameters derived from other studies (see Dincer and Rosen 2007) and are given as follows:

- For technology 1: gas turbine steam power cycle $\psi^{(1)} = 0.5$ and $D_p^{(1)} = 0.5$
- For technology 2: methane conversion $\psi^{(2)} = 0.8$ and $D_p^{(2)} = 0.2$

Therefore, the depletion number for separated technologies can be calculated by

$$D_p^{(\text{sep})} = \frac{W}{W + \text{Ex}_{\text{SG}}^0} D_p^{(1)} + \frac{\text{Ex}_{\text{SG}}^0}{W + \text{Ex}_{\text{SG}}^0} D_p^{(2)} = 0.33. \quad (16.6)$$

As observed by comparing the depletion numbers of separate and combined technologies, in the latter case (which corresponds to the industrial ecology approach) the depletion number is reduced by more than two times. The ratio between the depletion numbers in the two cases quantifies the amount of environment pollution and primary resource reduction that can be obtained.

Further, one can calculate how much higher must be the efficiencies of the separate technologies in order to equalize the combined technology performance. This can be done by equating $D_p^{(\text{comb})}$ with $D_p^{(\text{sep})}$. For example, one can keep $D_p^{(2)} = 0.2$ as a constant value and determine $D_p^{(1)} = 0.061$, which means that the exergy efficiency of gas turbine steam power cycle must be 0.94, which is not possible; the conclusion is that the separated technology approach can never reach the efficiency of the combined approach.

16.5 Concluding Remarks

The industrial ecology approach suggests designing industrial systems in an analogy with ecosystems, that is, with systems that can be observed from nature. Basically, as in nature, the wastes of one living species are used by other species as food or as natural biogeochemical cycles circulate chemicals in a closed loop, the industrial activities can minimize the resource consumption and waste production by using a combined approach of various technologies. Important ways of implementing industrial ecology include the appropriate combination of separate technologies in order to match the waste outputs of one with the inputs of the other, and the introduction of processes that reduce nonrenewable energy consumption. MFA is the basis of every industrial ecology design activity. This analysis must be complemented with thermo-energetic studies that account for the fluxes of energy and exergy.

Exergy analysis can help in designing industrial systems that follow the principles of industrial ecology, and in the evaluation of the efficiencies and losses for such activities. One such evaluation measure is the depletion number, which relates the exergy destruction and exergy input for a system. The example illustrated here compared the depletion numbers for separate and combined technologies as a means of assessing the effectiveness of the technology integration. The conducted analysis confirms that integrated energy systems, developed via an appropriate combination of technologies, represent an important opportunity for increasing the utilization efficiency of natural resources and thereby achieving the aims of industrial ecology.

Nomenclature

D_p	Depletion factor
$\dot{E}x$	Exergy rate, kW
$\dot{E}x_d$	Exergy destruction rate, kW
W	Work, kJ
\dot{W}	Work rate, kW

Greek Letter

ψ	Exergy efficiency
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Subscripts

D	Destruction
in	Input
out	Output
SG	Syngas

Superscripts

(comb)	Combined
(sep)	Separated

References

- Bringezu S., Moriguchi Y. 2002. Material flow analysis. In: *A Handbook of Industrial Ecology*, Ayres R.U., Ayres L.W., eds., Edward Elgar, Northampton, MA.
- Dincer I., Rosen M.A. 2007. Exergy and industrial ecology. In: *Exergy—Energy, Environment and Sustainable Development*. Elsevier, Oxford, UK, pp. 417-423.
- Frosch R.A., Gallopoulos N.E. 1989. Strategies for manufacturing. *Scientific American* 261:94–102.

- Harper E.M. 2008. A product-level approach to historical material flow analysis. Tungsten as a case study. *Journal of Industrial Ecology* 12:768–783.
- Saurat M., Bringezu S. 2008. Platinum group metal flows of Europe, Part I: Global supply, use in industry and shifting of environmental impacts. *Journal of Industrial Ecology* 12:754–767.
- Smil V. 2002. Global biogeochemical cycles. In: *A Handbook of Industrial Ecology*, Ayres R.U., Ayres L.W., eds., Edward Elgar, Northampton, MA.
- Strassert G. 2002. Physical input-output accounting. In: *A Handbook of Industrial Ecology*, Ayres R.U., Ayres L.W., eds., Edward Elgar, Northampton, MA.
- Tsunogai S., Igeuki K. 1968. Ammonia in the atmosphere. *Geochemical Journal* 2:157–166.
- White R. 1994. Preface. In: *The Greening of Industrial Ecosystems*, Allenby B.R., Richards D.J., eds., National Academy Press, Washington, DC.

Study Questions/Problems

- 16.1 Explain the concept of industrial ecology and its application.
- 16.2 Describe the natural carbon dioxide cycle.
- 16.3 Describe the nitrogen cycle and quantify the anthropogenic influence on it.
- 16.4 Describe the phosphorus cycle in nature.
- 16.5 Describe the sulfur cycle and the anthropogenic influence on it.
- 16.6 Explain the general industrial metal life cycle.
- 16.7 Explain plastic materials flow and recycling for product packaging.
- 16.8 Define the depletion number and comment on its usefulness.
- 16.9 Comment on the benefit of combining technologies.
- 16.10 What is the relationship between depletion number and exergy efficiency?
- 16.11 What is the effect of depletion number on resource sustainability?
- 16.12 Are the depletion numbers for renewable energy systems zero? Explain.
- 16.13 Obtain a published article on industrial ecology. Using the data provided in the article, try to duplicate the results. Compare your results to those in the original article.