Chapter 4

Exergy, environment, and sustainable development

Nomenclature

W	arithmetic weight assigned for an indicator
Y	dimensionless value of an indicator

Greek letters

η	nondimensional efficiency

Subscripts

ADP	abiotic depletion potential
AP	acidification potential
AT	air toxicity
EP	eutrophication potential
ER	nondimensional score of the efficiency
GWP	global warming potential
i	counter number of the dimensions
LU	land use
m	number of dimensions
ODP	ozone depletion potential
Pr	productivity
SA	smog air
WC	water consumption
WE	water ecotoxicity

Acronyms

CFC	chlorofluorocarbon
EIA	environmental impact assessment
LCA	life cycle assessment
MFA	material flux analysis
SPI	sustainable process index
VOC	volatile organic compound
WGM	weighted geometric mean

4.1 Introduction

The relationship between energy and economics was a prime concern in the 1970s. At that time, the linkage between energy and the environment did not receive much attention. As environmental concerns, such as acid rain, ozone depletion, and global climate change, became major issues in the 1980s, the linkage between energy utilization and the environment

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became more recognized. Since then, there has been increasing attention on this connection, as it has become more clear that energy production, transformation, transport, and use all impact the earth's environment, and that environmental impacts are associated with the thermal, chemical, and nuclear emissions which are a necessary consequence of the processes that provide benefits to humanity. Simultaneously, concerns have been expressed about the nonsustainable nature of human activities, and extensive efforts have been devoted to developing methods for achieving sustainable development.

The relation between sustainable development and the use of resources, particularly energy resources, is of great significance to societies. Attaining sustainable development requires that sustainable energy resources are being used, and is assisted if resources are used efficiently. Exergy methods are important since they are useful in improving efficiency. The relations between exergy and both energy and the environment makes it clear that exergy is directly related to sustainable development.

The fact that these topics are connected can be seen as relatively straightforward. For instance, the environmental impact of emissions can be reduced by increasing the efficiency of resource utilization. As this measure helps preserve resources, it is sometimes referred to as "*energy conservation*." However, increasing efficiency has sustainability implications as it lengthens the lives of existing resource reserves, but generally entails greater use of materials, labor, and more complex devices. Depending on the situation and the players involved, the additional cost may be justified by the added security associated with a decreased dependence on energy resources, by the reduced environmental impact and by the social stability obtained through increased productive employment.

Many suggest that mitigating the environmental impact of energy resource utilization and achieving increased resource-utilization efficiency are best addressed by considering exergy. By extension, since these topics are critical elements in achieving sustainable development, exergy also appears to provide the basis for developing comprehensive methodologies for sustainability. The exergy of an energy form or a substance is a measure of its usefulness or quality or the potential to cause change. The latter point suggests that exergy may be, or provide the basis for, an effective measure of the potential of a substance or energy form to impact the environment. In practice, the authors feel that a thorough understanding of exergy and the insights it can provide into the efficiency, environmental impact, and sustainability of energy systems, are required for the engineer or scientist working in the area of energy systems and the environment. Further, as energy policies increasingly play an important role in addressing sustainability issues and a broad range of local, regional, and global environmental concerns, policymakers also need to appreciate the exergy concept and its ties to these concerns. The need to understand the linkages between exergy and energy, sustainable development, and environmental impact has become increasingly significant.

Although many studies appeared during the past two decades concerning the close relationship between energy and the environment, there has only recently been an increasing number of works on the linkage between the exergy and the environment [1–8]. In this chapter, which extends ideas presented in our earlier works, we consider exergy as the confluence of energy, environment, and sustainable development, as illustrated in Fig. 4.1. The basis for this treatment is the interdisciplinary character of exergy and its relation to each of these disciplines. The primary objective of this chapter is to present a unified exergy-based structure that provides useful insights and direction to those involved in exergy, environment, and sustainable development for analyzing and addressing appropriately in each of these areas using the exergy concept.

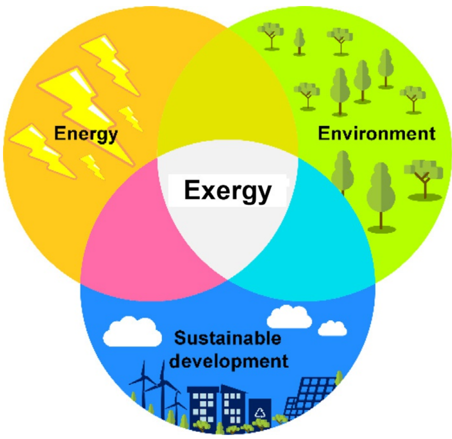


FIG. 4.1 Interdisciplinary triangle covered by the field of exergy analysis.

4.2 Exergy and environmental problems

4.2.1 Environmental concerns

Environmental problems, issues, and concerns span a continuously growing range of pollutants, hazards, and ecosystem degradation factors that affect areas ranging from local through regional to global. Some of these concerns arise from observable, chronic effects on, for instance, human health, while others stem from actual or perceived environmental risks such as possible accidental releases of hazardous materials.

Many environmental issues are caused by or relate to the production, transformation, and use of energy. For example, 11 major areas of environmental concern in which energy plays a significant role have been identified, namely, major environmental accidents, water pollution, maritime pollution, land use and siting impact, radiation and radioactivity, solid waste disposal, hazardous air pollutants, ambient air quality, acid deposition, stratospheric ozone depletion, and global climate change. While energy policy was concerned mainly with economic considerations in the 1970s and early 1980s, environmental-impact control, though clean fuels and energy technologies as well as energy efficiency, have received increasing attention over the last few decades.

Environmental problems are often complex and constantly evolving. Generally, our ability to identify and quantify scientifically the sources, causes, and effects of potentially harmful substances has greatly advanced. Throughout the 1970s, most environmental analyses and legal instruments of control focused on conventional pollutants (e.g., SO_x, NO_x, CO, and particulates). Recently, environmental control efforts have been extended to (i) hazardous air pollutants, which are usually toxic chemical substances that are harmful in small doses, and (ii) globally significant pollutants such as CO_2. Developments in industrial processes and systems often lead to new environmental problems. For instance, major increases in recent decades in the transport of industrial goods and people by car have led to increases in road traffic which, in turn, have enlarged the attention paid to the effects and sources of NO_x and volatile organic compounds (VOC) emissions.

Other important aspects of environmental impact are the effects of industrial devices on the esthetics and ecology of the planet. The relatively low costs of fossil fuels have made humanity increasingly dependent on them and caused significant pollution, endangering many biological systems, and reducing the planet's ecological diversity. Researchers and others can play a vital role in our planet's evolution by guiding the development of industrial society, in part by using exergy as a tool to reduce energy consumption and environmental degradation.

In the past few decades, the risks and reality of environmental degradation have become apparent. The environmental impact of human activities has grown due to the increasing world population, energy consumption, industrial activity, and so on. Details on pollutants and their impacts on the environment and humans may be found in [9]. The most internationally significant environmental issues are usually considered to be acid precipitation, stratospheric ozone depletion, and global climate change, which are the focus of this section.

4.2.1.1 Global climate change

Global climate change, including global warming, refers to the warming contribution of the earth of increased atmospheric concentration of CO_2 and other greenhouse gases. In Table 4.1, the contributions of various greenhouse gases to the

TABLE 4.1 Contributions of selected substances to global climate change.

Substance	ARIRR[a]	Atmospheric concentration (ppm)			AGR[b] (%)	SGEHA[c] (%)	SGEIHA[d] (%)
		Preindustrial	1990s	2020s			
CO_2	1	275	346	415	0.4	71	50 ± 5
CH_4	25	0.75	1.65	6.20	1	8	15 ± 5
N_2O	250	0.25	0.35	0.48	0.2	18	9 ± 2
R-11	17,500	0	0.00023	–	5	1	13 ± 3
R-12	20,000	0	0.00040	–	5	2	13 ± 3

[a]*Ability to retain infrared radiation relative to CO_2.*
[b]*Annual growth rate.*
[c]*Share in the greenhouse effect due to human activities.*
[d]*Share in the greenhouse effect increase due to human activities.*
Based on I. Dincer, M.A. Rosen, Energy, environment and sustainable development, Appl. Energy 64 (1–4) (1999) 427–440 and anonymous sources.

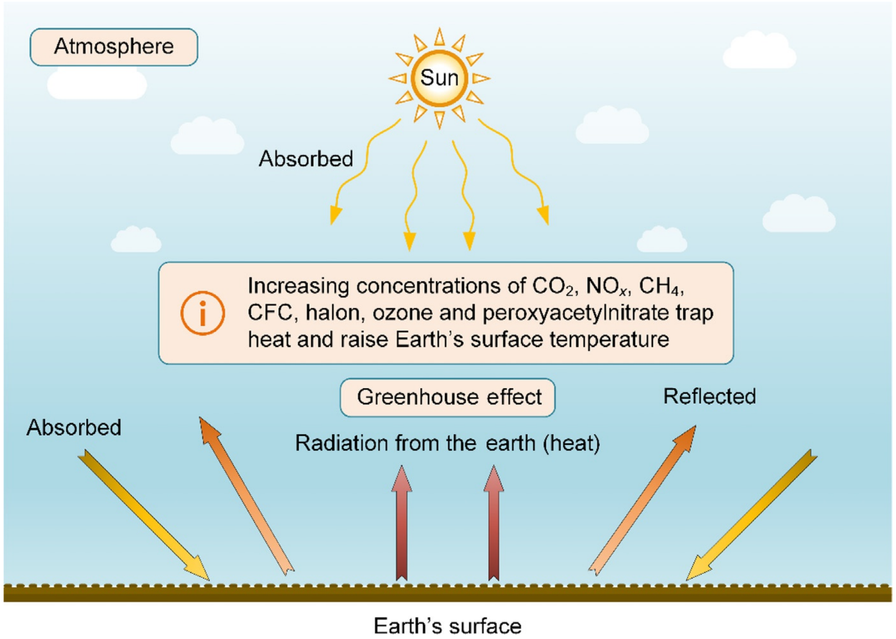


FIG. 4.2 Processes involved in the greenhouse effect.

processes involved in global climate change are summarized. CO_2 emissions account for about 50% of the anthropogenic greenhouse effect. Other gases such as methane (CH_4), chlorofluorocarbons (CFCs), halons, N_2O, ground ozone, and peroxyacetylnitrate, produced by industrial and domestic activities, also contribute to raising the earth's temperature (Fig. 4.2).

Global climate change is associated with increasing atmospheric concentrations of greenhouse gases, which trap heat radiated from the earth's surface, thereby raising the surface temperature of the earth. The earth's surface temperature has increased by about 1.0°C over the last century, and as a consequence, the sea level has risen by perhaps 20 cm or more. The role of various greenhouse gases is summarized in [7].

Humankind contributes to the increase in atmospheric concentrations of greenhouse gases. CO_2 released from fossil fuel combustion, methane emissions from human activity, chlorofluorocarbon releases, and deforestation all contribute to the greenhouse effect. Most scientists and researchers agree that emissions of greenhouse gases have led to global warming and that if atmospheric concentrations of greenhouse gases continue to increase, as present trends in fossil fuel consumption suggest, the earth's temperature may increase this century by 2 to 4°C. If this prediction is realized, the sea level could rise 30 to 60 cm by 2100, leading to flooding of coastal settlements, displacement of fertile zones for agriculture and food production toward higher latitudes, reduced freshwater for irrigation and other uses, and other consequences that could jeopardize populations. The magnitude of the greenhouse effect now and in the future is debated, but most agree that greenhouse gas emissions are to some extend harmful to the environment.

Most efforts to control global climate change must consider the costs of reducing carbon emissions. Achieving a balance between economic development and emissions abatement requires policies aimed at improving the efficiency of energy use, encouraging energy conservation and renewable energy use, and facilitating fuel switching (particularly to hydrogen), and increasing access to advanced technologies.

4.2.1.2 Stratospheric ozone depletion

Ozone in the stratosphere (altitudes of 12–25 km) absorbs ultraviolet (UV) radiation (wavelengths 240–320 nm) and infrared radiation. The regional depletion of the stratospheric ozone layer, which is caused by emissions of CFCs, halons (chlorinated and brominated organic compounds), and nitrogen oxides (NO_x) (Fig. 4.3), can lead to increased levels of damaging UV radiation reaching the ground, causing increased rates of skin cancer, eye damage, and other harm to biological species.

Many activities lead to stratospheric ozone depletion. CFCs, which are used in air conditioning and refrigerating equipment as refrigerants and in foam insulation as blowing agents, and NO_x emissions from fossil fuel and biomass combustion, natural denitrification, nitrogen fertilizers, and aircraft are the most significant contributors to ozone depletion. In 1987, an international landmark protocol was signed in Montreal to reduce the production of CFCs and halons, and commitments for further reductions and eventually banning were undertaken subsequently (e.g., the 1990 London Conference).

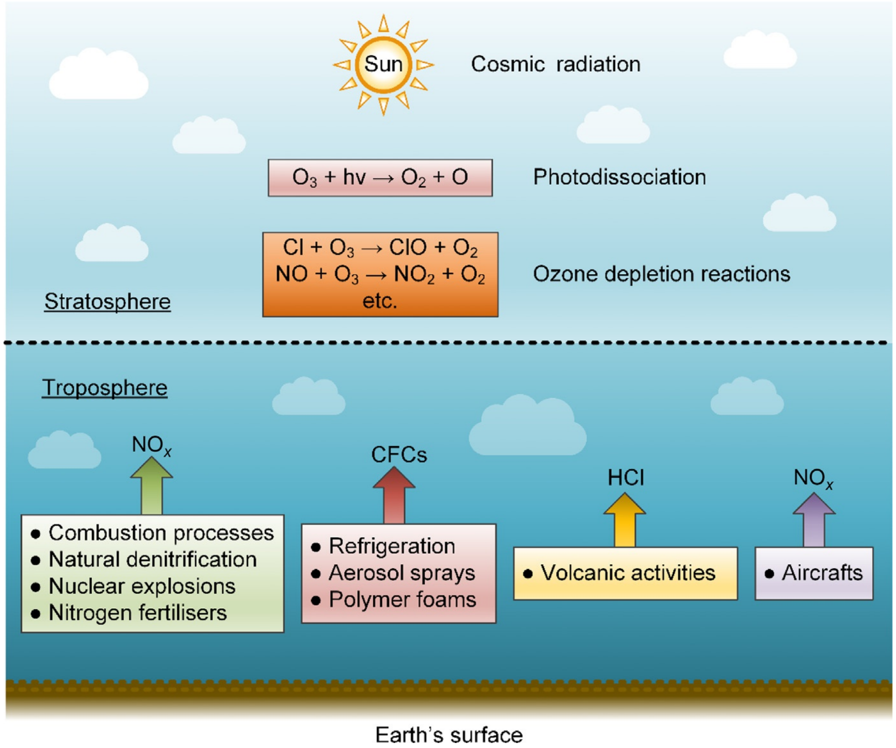


FIG. 4.3 Processes involved in stratospheric ozone depletion.

Researchers have studied the chemical and physical phenomena associated with ozone depletion, mapped of ozone losses in the stratosphere, and investigated the causes and impacts of the problem.

Alternative technologies that do not use CFCs have increased substantially and may allow for a total ban of CFCs. More time will be needed in developing countries, some of which have invested heavily in CFC-related technologies.

4.2.1.3 *Acid precipitation*

Acid rain (acid precipitation) is the result of emissions from the combustion of fossil fuels from stationary devices, such as smelters for nonferrous ores and industrial boilers, and vehicles. The emissions are transported through the atmosphere and deposited via precipitation on the earth. The acid precipitation from one country may fall on other countries, where it exhibits its damaging effects on the ecology of water systems and forests, infrastructure, and historical and cultural artifacts.

Acid rain is mainly attributable to emissions of SO_2 and NO_x which react with water and oxygen in the atmosphere to form such substances as sulfuric and nitric acids (Fig. 4.4). In the atmosphere, these substances react to form acids, which are sometimes deposited on ecosystems that are vulnerable to excessive acidity. The control of acid precipitation requires control of SO_2 and NO_x emissions. These pollutants cause local concerns related to health and contribute to the regional and trans-boundary problems of acid precipitation. Attention has also begun focusing on other contributing substances such as VOCs, chlorides, ozone, and trace metals, which may participate in chemical transformations in the atmosphere that result in acid precipitation and other pollutants.

The impacts of acid precipitation are as follows:

- acidification of lakes, streams, and ground waters,
- damage to forests, crops, and plants due to the toxicity of excessive acid concentration,
- harm to fish and aquatic life,
- deterioration of materials, e.g., buildings, metal structures, and fabrics, and
- alterations of the physical and optical properties of clouds due to the influence of sulfate aerosols.

Many energy-related activities lead to acid precipitation. Electric power generation, residential heating, and industrial energy use account for about 80% of SO_2 emissions. The sour gas treatment releases H_2S that reacts to form SO_2 when exposed to air. Most NO_x emissions are from fossil fuel combustion in stationary devices and road transport. VOCs from various sources contribute to acid precipitation. The largest contributors to acid precipitation are the United States, China,

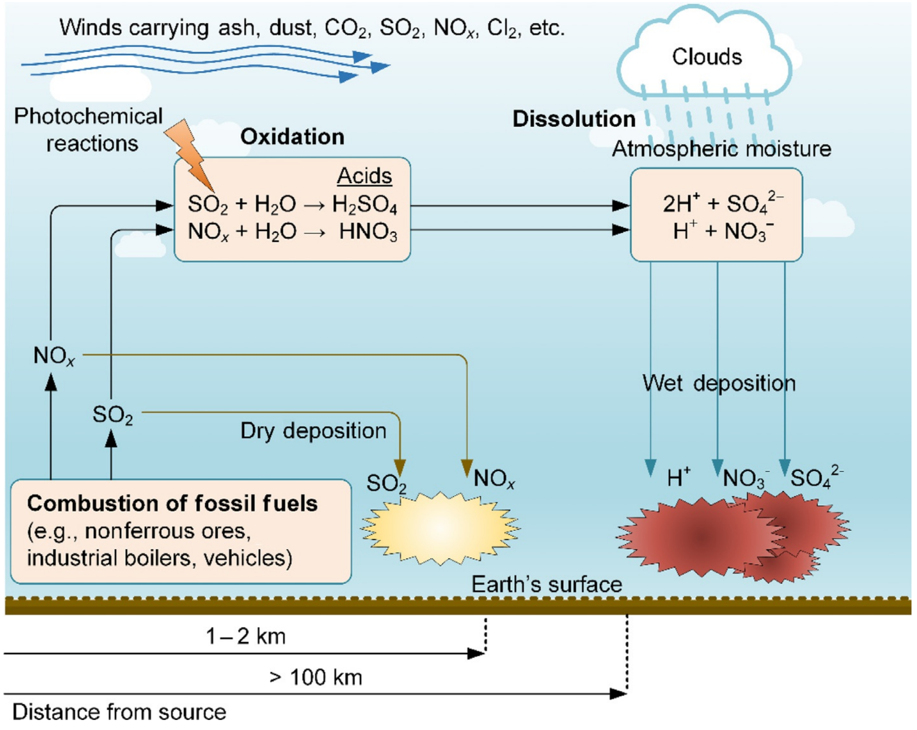


FIG. 4.4 Processes involved in the formation and transport of acid precipitation.

and the countries from the former Soviet Union. Some gaseous pollutants are listed in Table 4.2, along with their environmental impacts.

4.2.2 Potential solutions to environmental problems

Potential solutions to current environmental problems comprising pollutant emissions have recently evolved, including:

- Recycling
- Waste management
- Process change and sectoral modification
- Acceleration of forestation

TABLE 4.2 Impacts on the environment of selected gaseous pollutants.

Pollutants	Greenhouse effect	Stratospheric ozone depletion	Acid precipitation	Smog
Carbon monoxide (CO)	•	•	•	•
Carbon dioxide (CO_2)	+	+/–	•	•
Methane (CH_4)	+	+/–	•	•
Nitric oxide (NO) and Nitrogen dioxide (NO_2)	•	+/–	+	+
Nitrous oxide (N_2O)	+	+/–	•	•
Sulfur dioxide (SO_2)	–	+	•	•
Chlorofluorocarbons (CFCs)	+	+	•	•
Ozone (O_3)	+	•	•	+

Note: + denotes a contributing effect, – denotes that the substance exhibits an impact which varies with conditions and chemistry and may not be a general contributor, and • denotes no impact.
Based on J.G. Speight, Environmental Technology Handbook, Taylor & Francis, Washington, DC, 1996.

- Application of carbon and/or fuel taxes
- Materials substitution
- Promoting public transport
- Changing lifestyles
- Increasing public awareness of energy-related environmental problems
- Increased education and training
- Policy integration

Potential solutions to energy-related environmental concerns have also evolved. These include:

- Use of renewable energy technologies
- Use of advanced energy systems and applications
- Energy conservation and increasing the efficiency of energy utilization
- Application of cogeneration, trigeneration, and district heating and cooling, and hence multigenerational systems
- Use of alternative energy forms and sources for transport
- Smart grid
- Smart energy networks and distribution systems
- Energy-source switching from fossil fuels to environmentally benign energy forms
- Use of energy storage technologies
- Use of clean coal technologies
- Use of clean fuel technologies
- Use of artificial intelligence, machine learning, and data management techniques
- Internet of things
- Optimum monitoring and evaluation of energy indicators

Among the potential solutions listed previously, some of the most important are the use of renewable and advanced energy technologies. An important step in moving toward the implementation of such technologies is to identify and remove barriers. Several barriers have in the past been identified to the development and introduction of cleaner energy processes, devices, and products. The barriers can also affect the financing of efforts to augment the supply of renewable and advanced energy technologies.

Some of the barriers faced by many renewable and advanced energy technologies include:

- technical constraints,
- financial constraints,
- limited information and knowledge of options,
- lack of necessary infrastructure for recycling, recovery, and reuse of materials and products,
- lack of facilities,
- lack of expertise within industry and research organizations, and/or lack of coordinated expertise,
- poorly coordinated and/or ambiguous national aims related to energy and the environment,
- uncertainties in government regulations and standards,
- lack of adequate organizational structures,
- lack of differentiated electrical rates to encourage off-peak electricity use,
- mismanagement of human resources,
- lack of social acceptability of new renewable and advanced energy technologies,
- absence of, or limited consumer demand for, renewable and advanced energy products and processes.

Establishing useful methods for promoting renewable and advanced energy technologies requires analysis and clarification about how to combine environmental objectives, social and economic systems, and technical development. It is important to employ tools that encourage technological development and diffusion and to align government policies in energy and the environment.

4.2.3 Energy and environmental impact

Energy resources are required to supply the basic human needs of food, water, and shelter, and to improve the quality of life. The United Nations indicates that the energy sector must be addressed in any broad atmosphere-protection strategy, through programs in two major areas: increasing energy efficiency and shifting to environmentally sound energy systems.

The major areas investigated promote: (i) the energy transition, (ii) increased energy efficiency and, consequently, increased exergy efficiency, (iii) renewable energy sources, and (iv) sustainable transportation systems. It was reported that (i) a major energy efficiency program would provide an important means of reducing CO_2 emissions, and (ii) the activities should be accompanied by measures to reduce the fossil fuel component of the energy mix and to develop alternative energy sources. These ideas have been reflected in many recent studies concentrating on the provision of energy services with the lowest reasonable environmental impact and cost and the highest reasonable energy security.

Waste heat emissions to the environment are also of concern, as irresponsible management of waste heat can significantly increase the temperature of portions of the environment, resulting in thermal pollution. If not carefully controlled so that local temperature increases are kept within safe and desirable levels, thermal pollution can disrupt marine life and ecological balance in lakes and rivers.

Measures to increase energy efficiency can reduce environmental impact by reducing energy losses. Within the scope of exergy methods, as discussed in the next section, such activities lead to increased exergy efficiency and reduced exergy losses (both waste exergy emissions and internal exergy consumptions). In practice, potential efficiency improvements can be identified through modeling and computer simulation. Increased efficiency can help achieve energy security in an environmentally acceptable way by reducing the emissions that might otherwise occur. Increased efficiency also reduces the requirement for new facilities for the production, transportation, transformation, and distribution of the various energy forms, and the associated environmental impact of these additional facilities. To control pollution, efficiency improvement actions often need to be supported by pollution amelioration technologies or fuel substitution. The most significant measures for environmental protection are usually those undertaken at the regional or national levels, rather than by individual projects.

4.2.4 Thermodynamics and the environment

People have long been intrigued by the implications of the laws of thermodynamics on the environment. One myth speaks of Ouroboros, a serpent-like creature that survived and regenerated itself by eating only its own tail. By neither taking from nor adding to its environment, this creature was said to be completely environmentally benign and self-sufficient. It is useful to examine this creature in light of the thermodynamic principles recognized today. Assuming that Ouroboros was an isolated system (i.e., it received no energy from the sun or the environment, and emitted no energy during any process), Ouroboros' existence would have violated neither the conservation law for mass nor the first law of thermodynamics (which states energy is conserved). However, unless it was a reversible creature, Ouroboros' existence would have violated the second law (which states that exergy is reduced for all real processes), since Ouroboros would have had to obtain exergy externally to regenerate the tail it ate into an equally ordered part of its body (or it would ultimately have dissipated itself to an unordered lump of mass). Thus, Ouroboros would have to have an impact on its environment.

Besides demonstrating that, within the limits imposed by the laws of thermodynamics, all real processes must have some impact on the environment, this example is intended to illustrate the following key point: the second law is instrumental in providing insights into environmental impact [5, 10, 11]. Today, the principles demonstrated through this example remain relevant, and technologies are sought having Ouroboros's characteristics of being environmentally benign and self-sufficient (e.g., University of Minnesota researchers built an "energy-conserving" house called Ouroboros [12]. The importance of the second law in understanding environmental impact implies that exergy, which is based on the second law, has an important role to play in this field.

The most appropriate link between the second law and environmental impact has been suggested to be exergy [5], in part because it is a measure of the departure of the state of a system from that of the environment. The magnitude of the exergy of a system depends on the states of both the system and the environment. This departure is zero only when the system is in equilibrium with its environment. The concept of exergy analysis as it applies to the environment is discussed in detail elsewhere [5].

An understanding of the relations between exergy and the environment may reveal the underlying fundamental patterns and forces affecting changes in the environment, and help researchers deal better with environmental damage. Tribus and McIrvine [13] suggest that performing exergy analyses of the natural processes occurring on the earth could form a foundation for ecologically sound planning because it would indicate the disturbance caused by large-scale changes. Three relationships between exergy and environmental impact [5] are discussed in the following section:

- *Order destruction and chaos creation.* The destruction of order, or the creation of chaos, is a form of environmental damage. Entropy is fundamentally a measure of chaos and exergy of order. A system of high entropy is more chaotic or disordered than one of low entropy and relative to the same environment, the exergy of an ordered system is greater than that of a chaotic one. For example, a field with papers scattered about has higher entropy and lower exergy than the field with the papers neatly piled. The exergy difference of the two systems is a measure of (i) the exergy (and order) destroyed when the wind scatters the stack of papers, and (ii) the minimum work required to convert the chaotic system to the ordered one (i.e., to collect the scattered papers). In reality, more than this minimum work, which only applies if a reversible cleanup process is employed, is required. The observations that people are bothered by a landscape polluted with papers chaotically scattered about, but value the order of a clean field with the papers neatly piled at the side, suggests that, on a more abstract level, ideas relating exergy and order in the environment may involve human values [11] and that human values may in part be based on exergy and order.

- *Resource degradation.* The degradation of resources found in nature is a form of environmental damage. Kestin [14] defines a resource as a material, found in nature or created artificially, which is in a state of disequilibrium with the environment, and notes that resources have exergy as a consequence of this disequilibrium. Two main characteristics of resources are valued:
  - composition (e.g., metal ores). Many processes exist to increase the value of such resources by purifying them, which increases their exergy. Note that purification is accomplished at the expense of consuming at least an equivalent amount of exergy elsewhere (e.g., using coal to drive metal ore refining).
  - Reactivity (e.g., fuels), i.e., their potential to cause change, or "drive" a task or process.

  Two principal general approaches exist to reduce the environmental impact associated with resource degradation:
  - Increased efficiency. Increased efficiency preserves exergy by reducing the exergy necessary for a process, and, therefore, reduces environmental damage. Increased efficiency also usually reduces exergy emissions which, as discussed in the next section, also play a role in environmental damage.
  - Using external exergy resources (e.g., solar energy). The earth is an open system subject to a net influx of exergy from the sun. It is the exergy (or order states) delivered with solar radiation that is valued; all the energy received from the sun is ultimately radiated out to the universe. Environmental damage can be reduced by taking advantage of the openness of the earth and utilizing solar radiation (instead of degrading resources found in nature to supply exergy demands). This would not be possible if the earth was a closed system, as it would eventually become more and more degraded or "entropic."
- *Waste exergy emissions.* The exergy associated with waste emissions can be viewed as a potential for environmental damage in that the exergy of the wastes, as a consequence of not being in stable equilibrium with the environment, represents a potential to cause change. When emitted to the environment, this exergy represents the potential to change the environment. Usually, emitted exergy causes a change which is damaging to the environment, such as the deaths of fish and plants in some lakes due to the release of specific substances in stack gases as they react and come to equilibrium with the environment, although in some cases the change may be perceived to be beneficial (e.g., the increased growth rate of fish and plants near the cooling-water outlets from thermal power plants). Further, exergy emissions to the environment can interfere with the net input of exergy via solar radiation to the earth (e.g., emissions of CO_2 and other greenhouse gases from many processes appear to cause changes to the atmospheric CO_2 concentration, affecting the receiving and reradiating of solar radiation by the earth). The relation between waste exergy emissions and environmental damage has been recognized by several researchers [1]. By considering the economic value of exergy in fuels, Reistad developed an air-pollution rating that he felt was preferable to the mainly empirical ratings then in use, in which the air-pollution cost for fuel was estimated as either (i) the cost to remove the pollutant or (ii) the cost to society of the pollution in the form of a tax which should be levied if pollutants are not removed from effluent streams.

Although the previous two points indicate simultaneously that exergy in the environment in the form of resources is of value while exergy in the environment in the form of emissions is harmful due to its potential to cause environmental damage, confusion can be avoided by considering whether or not the exergy is constrained (see Fig. 4.5).

Most resources found in the environment are constrained and by virtue of their exergy are of value, while unconstrained emissions of exergy are free to impact in an uncontrolled manner on the environment. To elaborate further on this point, consider a scenario in which emissions to the environment are constrained (e.g., by separating sulfur from stack gases). This action yields two potential benefits: the potential for environmental damage is restrained from entering the environment, and the now-constrained emission potentially becomes a valued commodity, i.e., a source of exergy.

The decrease in the environmental impact of a process, in terms of several measures, as the process exergy efficiency increases is illustrated approximately in Fig. 4.6.

4.3 Exergy and sustainable development

Energy resources are needed for societal development, and sustainable development requires a supply of energy resources that is sustainably available at a reasonable cost and causes no or minimal negative societal impacts. Energy resources such

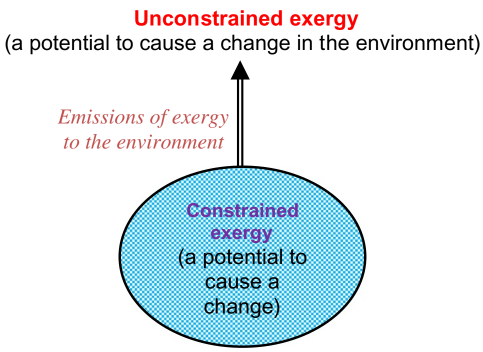


FIG. 4.5 Comparison of constrained and unconstrained exergy illustrating that exergy constrained in a system represents a resource, while exergy emitted to the environment becomes unconstrained and represents a driving potential for environmental damage.

as fossil fuels are finite and thus lack the characteristics needed for sustainability, while others such as renewable energy sources are sustainable over the relatively long term. Environmental concerns are also a major factor in sustainable development, as activities that degrade the environment are not sustainable. Since much environmental impact is associated with energy use, sustainable development requires the use of energy resources which cause as little environmental impact as reasonably possible. Limitations on sustainable development due to environmental emissions can be in part overcome through increased efficiency, as this usually leads to less environmental impact for the same services or products.

The diversity of energy choices is but one reason why exergy plays a key role in the context of sustainable development.

Many factors contribute toward achieving sustainable development. For example, for development to be sustainable:

- it must satisfy the needs and aspirations of society,
- it must be environmentally and ecologically benign, and
- sufficient resources (natural and human) must be available.

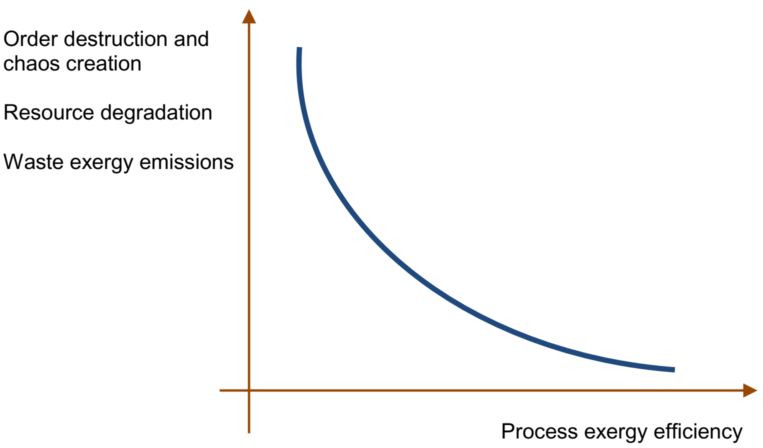
The second point reinforces the importance of environmental concerns in sustainable development. Activities that continually degrade the environment are not sustainable over time, while those that have no or little negative impact on the environment are more likely to contribute to sustainable development (provided, of course, that they satisfy the other conditions for sustainable development).

4.3.1 Sustainable development

The term *sustainable development* was introduced in 1980, popularized in the 1987 report of the World Commission on Environment and Development (the Brundtland Commission), and given a global mission status by the UN Conference on Environment and Development in Rio de Janeiro in 1992.

The Brundtland Commission defined *sustainable development* as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The Commission noted that its definition

FIG. 4.6 Qualitative illustration of the relation between the exergy efficiency of a process and the associated environmental impact in terms of order destruction and chaos creation, or resource degradation, or waste exergy emissions.



contains two key concepts: *needs*, meaning "in particular the essential needs of the world's poor," and *limitations*, meaning "limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs" [15].

The Brundtland Commission's definition was thus not only about sustainability and its various aspects but also about equity, equity among present inhabitants of the planet, and equity among generations. *Sustainable development* for the Brundtland Commission includes environmental, social, and economic factors, but considers remediation of current social and economic problems an initial priority. The chief tools cited for remediation are "more rapid economic growth in both industrial and developing countries, freer market access for the products of developing countries, greater technology transfer, and significantly larger capital flows, both concessional and commercial." Such growth was said to be compatible with recognized environmental constraints, but the extent of the compatibility was not explored.

An enhanced definition of global sustainable development is presented in the Encyclopedia of Life Support Systems [16] "*the wise use of resources through critical attention to policy, social, economic, technological, and ecological management of natural and human engineered capital so as to promote innovations that assure a higher degree of human needs fulfillment, or life support, across all regions of the world, while at the same time ensuring intergenerational equity*."

4.3.2 Sustainability and its need

The world is changing rapidly due in part to the increasing wealth and size of the population. A growing need exists for more efficient and sustainable production processes. As our world increasingly strives for a more sustainable society, we must overcome some major problems, e.g., increasing population, lack of and inequitable distribution of wealth, insufficient food production and energy supply, and increasing environmental impact.

Sustainability has been called a key in solving current ecological, economic, and developmental problems. Sustainability has been broadly discussed since it was brought to public attention by the Brundtland Report and has since been developed into a blueprint for reconciling economic and ecological necessities. Many have contributed to making this concept scientifically acceptable so that it can be utilized as a yardstick for strategic planning. Two features that make sustainability useful for strategic planning are its inherent long-term view and its ability to accommodate changing conditions.

Sustainability and *sustainable development* became fashionable terms in the 1990s, a legacy of concerns about the environment expressed during the 1970s and 1980s. The media often refer to the same concepts via such terms sustainable architecture, sustainable food production, sustainable future, sustainable community, sustainable economic development, sustainable policy, and so on.

Some key component requirements for sustainable development (see Fig. 4.7) are societal, economic, environmental, and technological sustainability. Some topics within each of these component areas are listed in this figure as well.

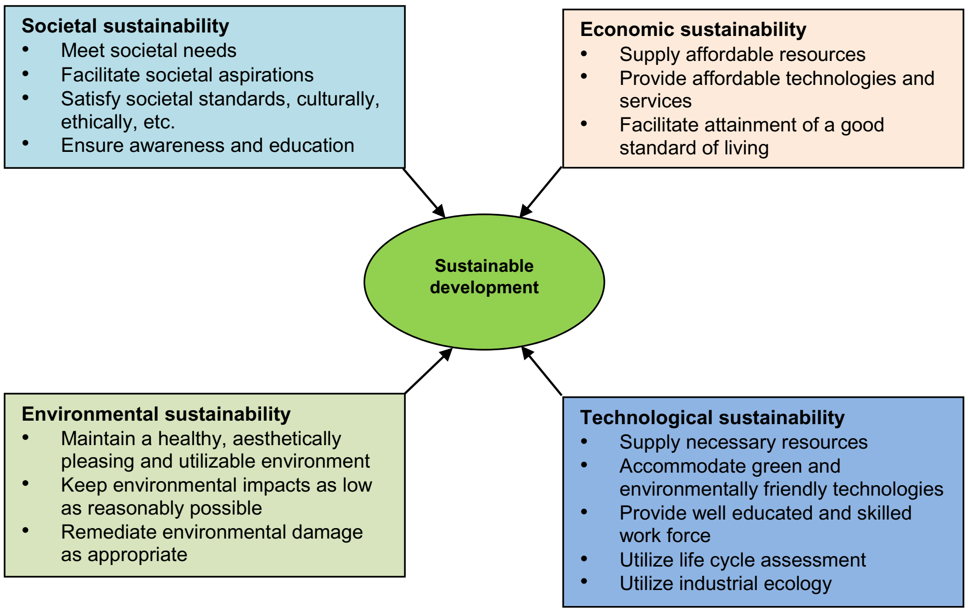


FIG. 4.7 Some key requirements to consider for sustainable development.

4.3.3 Dimensions of sustainability

The kinds of techno-economic changes envisaged by many as necessary for long-term sustainability usually include sharp reductions in the use of fossil fuels to minimize the danger of global climate change. Alternatives to using fossil fuels include the use of nuclear power, large-scale photovoltaics, intensive biomass cultivation and large-scale hydroelectric projects (in applicable regions), as well as major changes in patterns of energy consumption and conservation. Again, there are disputes over which of these energy alternatives is the most desirable, feasible, and so on. However, understanding future energy patterns, from both supply and demand perspectives, is critical [17].

The ecological criterion for sustainability acknowledges the likelihood that some important functions of the natural environment cannot be replaced within any realistic time-frame, if ever, by human technology, however, sophisticated. Some examples include the need for arable land, water, and a benign climate for agriculture, the role of reducing bacteria in recycling nutrient elements in the biosphere, and the protection provided by the stratospheric ozone layer. The ecological criterion for long-term sustainability implicitly allows for some technological intervention. For example, methods of artificially accelerating tree growth may compensate for some net decrease in the land area devoted to forests. However, in the absence of any plausible technological fixes, sustainability does not allow for major climate change, widespread desertification, deforestation of the tropics, accumulation of toxic heavy metals, and nonbiodegradable halogenated organics in soils and sediments, sharp reductions in biodiversity, and so on.

4.3.4 Environmental limits and geographic scope

The report of the Brundtland Commission stimulated debate not only about the environmental impacts of industrialization and the legacy of present activities for coming generations but also about what might be the physical or ecological limits to economic growth. From this perspective, sustainability can be defined in terms of carrying capacity of the ecosystem and described with input-output models of energy and resource consumption. Sustainability then becomes an economic state where the demands placed on the environment by people and commerce can be met without reducing the capacity of the environment to provide for future generations. Some [18–21] have expressed this idea in simple terms as an economic rule for a restorative economy as: "*Leave the world better than you found it, take no more than you need, try not to harm life or the environment, make amends if you do*."

Sustainability-related limits on society's material and energy throughputs might be set as follows [15]:

- The rates of use of renewable resources should not exceed their rates of regeneration.
- The rates of use of nonrenewable resources should not exceed the rates at which renewable substitutes are developed.
- The rates of pollutant emissions should not exceed the corresponding assimilative capacity of the environment.

Sustainability or unsustainability must also be considered in terms of geographic scope. Some activities may be globally unsustainable. For example, they may result in climate change or depletion of the stratospheric ozone layer, and so affect several geographic regions, if not the whole world. Other activities may be regionally unsustainable, perhaps by producing and dispersing tropospheric ozone or acidifying gases that can kill vegetation and cause famine in one region but not in other parts of the world. Still, other activities may be locally unsustainable, perhaps because they lead to hazardous ambient levels of CO locally or because the noise they produce makes habitation impossible. Overall, sustainability appears to be more global than a regional or local concern. If an environmental impact exceeds the carrying capacity of the planet, for instance, then life is threatened, but it is beyond the carrying capacity of one area, then that area may become uninhabitable but life can most likely continue elsewhere.

4.3.5 Environmental, social, and economic components of sustainability

The focus of this discussion on physical limits does not ignore the social and economic aspects of sustainability. Some may consider a way of life that may not worth sustaining under certain circumstances, such as extreme oppression or deprivation. Oppression or deprivation can interfere with efforts to make human activity environmentally benign. Nonetheless, if ecosystems are irreparably altered by human activity, then subsequent human existence may become not merely unpalatable, but infeasible. Thus the environmental component of sustainability is essential.

The heterogeneity of the environmental, social, and economic aspects of sustainability should also be recognized. Environmental and social considerations often refer to *ends*, the former having perhaps more to do with the welfare of future generations and the latter with the welfare of present people. Rather than an end, economic considerations can perhaps more helpfully be seen as a *means* to the various ends implied by environmental and social sustainability.

4.3.6 Industrial ecology and resource conservation

In the field of industrial ecology, Connelly and Koshland [22] have stated that the several processes that de-link consumption from depletion in evolving biological ecosystems can be used as resource-conservation *strategies* for de-linking consumption from depletion in immature industrial systems. These processes include waste cascading, resource cycling, increasing exergy efficiency, and renewable exergy use.

Connelly and Koshland [22, 23] demonstrate that the relation between these strategies and an exergy-based definition they propose for ecosystem evolution follows directly from first- and second-law principles. They discuss the four conservation strategies in the context of a simple, hypothetical industrial ecosystem consisting initially of two solvent consumption processes and the chain of industrial processes required to deliver solvent to these two processes. One solvent consuming process is assumed to require lower purity feedstock than the other. All solvent feedstocks are derived from nonrenewable, fossil sources, and all solvent leaving the two consumptive processes is emitted to the atmosphere. This is a linear process that takes in useful energy and materials and releases waste energy and material.

- **Waste cascading:** Waste cascading may be described in thermodynamic terms as using outputs from one or more consumptive processes as inputs to other consumptive processes requiring equal or lower exergy. Waste cascading reduces resource consumption in two ways: by reducing the rate of exergy loss caused by the dissipation of potentially usable wastes in the environment, and by reducing the need to refine virgin resources. In our hypothetical industrial ecosystem, cascading allows used (i.e., partially consumed) solvent from the first process to be used in the second solvent consumption process, eliminating solvent emissions from the first process and the need to refine and supply pure solvent to the second process. The solvent consumption rate in the two processes is unchanged, but the rate of resource depletion associated with these processes is reduced. Although waste cascading reduces demand for other resources and hence is an important resource conservation strategy, cascading does not return to waste the exergy that was removed from it during its use. Thus, cascading cannot form a resource cycle. Losses associated with the upgrade and supply of solvent to the top of the cascade, the consumption of resources in the two processes constituting the cascade, and dissipation of waste solvent released from the bottom of the cascade cannot be avoided. Cascading can thus reduce the linkage between consumption and depletion, but it cannot fully de-link the two.
- **Resource cycling:** To reduce emissions from the bottom of a waste cascade (or at the outlet of a single consumptive process) and return this bottom waste to the top of a resource cascade, the exergy removed from a resource during consumption must be returned to it. This process of exergy loss through consumption followed by exergy return through transfer is the basis of resource cycling. Adding a solvent recycling process and its associated chain of industrial processes to the hypothetical system reduces depletion both by eliminating exergy loss from the dissipation of released solvents and by substituting a postconsumption upgrade path for a virgin resource upgrade path. An activated carbon solvent separation system, for example, will generally be far less exergy intensive than the fossil-based manufacture of virgin solvent. Cycling cannot, however, eliminate depletion. Following the second law, all exergy transfers in real (irreversible) processes must be accompanied by exergy loss (i.e., total exergy must always decrease). Hence, in any real cycling process, the overall resource depletion rate will exceed the rate of exergy loss in the consumptive process whose wastes are being cycled. In the previously mentioned example, the two solvent consumption processes and the exergy removed from nonrenewed resources to upgrade the solvent would contribute to resource depletion in the case of complete solvent cycling.
- **Increasing exergy efficiency:** One way to reduce the resource depletion associated with cycling is to reduce the losses that accompany the transfer of exergy to consumed resources by increasing the efficiency of exergy transfer between resources (i.e., increasing the fraction of exergy removed from one resource that is transferred to another). Exergy efficiency may be defined as

$$\textit{Exergy efficiency} = \textit{Exergy output}/\textit{Exergy input}$$

where

$$\textit{Exergy loss} = \textit{Exergy input} - \textit{Exergy output}$$

Compared to energy efficiency, exergy efficiency may be thought of as a more meaningful measure of efficiency that accounts for quantity *and* quality aspects of energy flows. Unlike energy efficiency, exergy efficiency provides an *absolute* measure of efficiency that accounts for first- and second-law limitations. In the current example, increasing exergy efficiency in the case of complete cycling would involve increasing the efficiency of the solvent upgrade process. Although technological and economic limitations to efficiency gains prevent exergy efficiency from approaching unity, many industrial processes today operate at very low efficiencies, and it is widely recognized that large margins for efficiency improvement often remain. However, even if exergy efficiency could be brought to 100%, the resource depletion associated with solvent consumption and upgrade in the example would still not be eliminated. Recycling with a 100% exergy efficient upgrade process would result in a depletion rate equal to the consumption rate of the two solvent consumption processes. To fully de-link consumption from depletion, it is necessary to use resources that supply exergy without being depleted.

- **Renewable exergy use:** To fully de-link consumption from depletion, the exergy used to upgrade consumption products must be derived from renewable exergy sources (i.e., sources such as electricity generated directly or indirectly from solar radiation or sources such as sustainably harvested biomass feedstocks). In the solvent cycling example, using a sustainably harvested biomass fuel as the exergy source for the solvent upgrade process could in theory create a solvent cycling system in which a closed solvent cycle is driven entirely by renewable exergy inputs. In this situation, the depletion rate becomes independent of the exergy efficiency of the solvent upgrade process.

4.3.7 Energy and sustainable development

The relation between sustainable development and the use of resources, particularly energy resources, is of great significance to societies [24, 25]. A supply of energy resources is generally agreed to be necessary, but not sufficient, the requirement for development within society. Societies, such as countries or regions that undergo significant industrial and economic development almost always have access to a supply of energy resources. In some countries (e.g., Canada) energy resources are available domestically, while in others (e.g., Japan) they must be imported.

For development that is sustainable over long periods, there are further conditions that must be met. Principally, such societies must have access to and utilize energy resources that are sustainable in a broad sense, i.e., that are obtainable securely and reliably, safely utilizable to satisfy the energy services for which they are intended with minimal negative environmental, health and societal impacts, and usable at reasonable costs.

An important implication of the previously mentioned statements is that sustainable development requires not just that sustainable energy resources be used, but that the resources be used efficiently. Exergy methods are essential in evaluating and improving efficiency. Through efficient utilization, society maximizes the benefits it derives from its resources while minimizing the negative impacts (such as environmental damage) associated with their use. This implication acknowledges that most energy resources are to some degree finite so that greater efficiency in utilization allows such resources to contribute to development over a longer period, i.e., to make development more sustainable. Even if one or more energy resources eventually become inexpensive and widely available, increases in energy efficiency will likely remain sought to reduce the associated environmental impacts, and the resource requirements (energy, material, and so on.) to create and maintain systems to harvest the energy.

4.3.8 Energy and environmental sustainability

The environmental aspects of energy use merit further consideration, as a large portion of the environmental impact in society is associated with energy-resource utilization. Ideally, a society seeking sustainable development utilizes only energy resources which cause no environmental impact. Such a condition can be attained or nearly attained by using energy resources in ways that cause little or no wastes to be emitted into the environment, and/or that produce only waste emissions that have no or minimal negative impact on the environment. This latter condition is usually met when relatively inert emissions that do not react in the environment are released, or when the waste emissions are in or nearly in equilibrium (thermal, mechanical, and chemical) with the environment, i.e., when the waste exergy emissions are minimal.

In reality, however, all resource use leads to some degree of environmental impact. A direct relation exists between exergy efficiency (and sometimes energy efficiency) and environmental impact, in that through increased efficiency, a fixed level of services can be satisfied with fewer energy resources and, in most instances, reduced levels of related waste emissions. Therefore, it follows that the limitations imposed on sustainable development by environmental emissions and their negative impacts can be in part overcome through increased efficiency, i.e., increased efficiency can make development more sustainable.

4.3.9 Exergy and sustainability

Exergy can be considered the confluence of energy, environment, and sustainable development, as shown in Fig. 4.1, which illustrates the interdisciplinary character of exergy and its central focus among these disciplines.

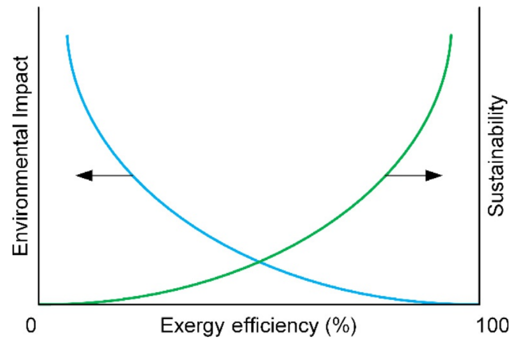


FIG. 4.8 Qualitative illustration of the relation between the environmental impact and sustainability of a process, and its exergy efficiency.

Exergy methods can be used to improve sustainability. For example, in a recent study on thermodynamics and sustainable development, Cornelissen [26] points out that one important element in obtaining sustainable development is the use of exergy analysis. By noting that energy can never be "lost," as it is conserved according to the first law of thermodynamics, while exergy can be lost due to internal irreversibilities, that study suggests that exergy losses, particularly due to the use of nonrenewable energy forms, should be minimized to obtain sustainable development. Further, the study shows that environmental effects associated with emissions and resource depletion can be expressed in terms of one exergy-based indicator, which is founded on physical principles.

Sustainable development also includes economic viability. Thus, the methods relating to exergy and economics also reinforce the link between exergy and sustainable development. The objectives of most existing analysis techniques integrating exergy and economics include the determination of (i) the appropriate allocation of economic resources to optimize the design and operation of a system, and/or (ii) the economic feasibility and profitability of a system. Exergy-based economic analysis methods are referred to by such names as thermoeconomics, second-law costing, cost accounting, and exergoeconomics.

Fig. 4.8 illustratively presents the relation between exergy and sustainability and environmental impact. There, sustainability is seen to increase and environmental impact to decrease as the process exergy efficiency increases. The two limiting efficiency cases are significant. First, as exergy efficiency approaches 100%, environmental impact approaches zero, since exergy is only converted from one form to another without loss, either through internal consumptions or waste emissions. Also, sustainability approaches infinity because the process approaches reversibility. Second, as exergy efficiency approaches 0%, sustainability approaches zero because exergy-containing resources are used but nothing is accomplished. Also, environmental impact approaches infinity because, to provide a fixed service, an ever-increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes are emitted.

Some important contributions, that can be derived from exergy methods, for increasing the sustainability of development which is nonsustainable are presented in Fig. 4.9. Development typical of most modern processes, which are generally nonsustainable, is shown at the bottom of the figure. A future in which development is sustainable is shown at the top of the figure, while some key exergy-based contributions toward making development more sustainable are shown, and include increased exergy efficiency, reduction of exergy-based environmental degradation, and use of sustainable exergy resources.

4.3.10 Exergetic aspects of sustainable processes

Fig. 4.10 outlines a typical industrial process, with its throughputs of materials and energy. Cleaner production of materials, goods, and services is one of the tools for sustainable development. Such production entails the efficient use of resources and the corresponding production of only small amounts of waste. Clean production often also involves the use of renewable resources. Yet the quality of the products remains important. This does not mean that cleaner production is necessarily contradictory to the economic approach of minimizing costs and maximizing profits. The challenge is often to generate win-win situations, such as those that, by minimizing the use of resources and the corresponding emissions, also decrease the costs of a given process.

As mentioned earlier, life cycle assessment (LCA) aims to improve or to optimize processes so that they consume fewer resources and produce fewer emissions and wastes. Common routes for achieving this often include end-of-pipe treatment such as wastewater treatment plants, filters, and scrubbers. These provide only partial solutions, as they do not decrease the environmental load, but rather shift it from one phase and location to another, e.g., water or air to soil. In many cases,

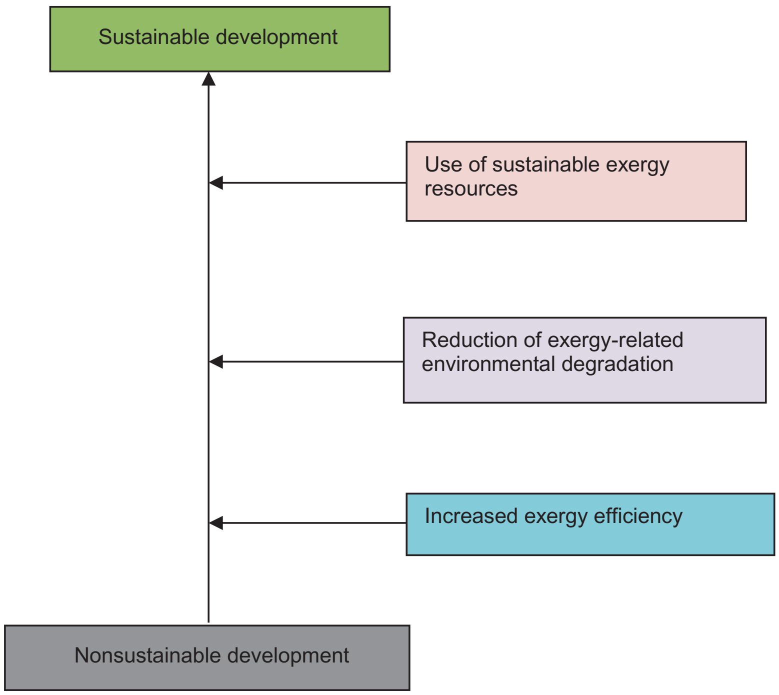


FIG. 4.9 Some key contributions of exergy methods for increasing the sustainability of nonsustainable systems and processes.

however, expensive end-of-pipe treatment solutions are unavoidable. Exergy analysis appears to be a significant tool for improving processes by changing their characteristics, rather than simply via end-of-pipe fixes. Thus exergy methods can help achieve more sustainable processes.

As a basic example, consider the conversion of mechanical work to heat ideally, i.e., with 100% efficiency. The heat has lower exergy or quality than work. Therefore, heat cannot be converted to work with a 100% energy efficiency. But, the conversion can be in theory achieved with a 100% exergy efficiency. Thus exergy analysis helps identify the upper limit for efficiency improvements.

Some examples of the difference between energy and exergy are shown in Table 4.3. Hot water and steam with the same enthalpy have different exergy, the value for steam being higher than for hot water. Fuels like natural gas and gasoline have exergetic values comparable to their net heating values. Work and electricity have the same exergy and energy. Exergy is calculated in Table 4.3 as the product of energy and a quality factor.

4.3.11 Renewables and tools for sustainable development

Renewable energy resources are often sustainable. Most energy supplies on earth derive from the sun, which continually warms us and supports plant growth via photosynthesis. Solar energy heats the land and sea differentially and so causes winds and consequently waves. Solar energy also drives evaporation, which leads to rain and, in turn, hydropower. Tides are the result of the gravitational pull of the moon and sun and geothermal heat is the result of radioactive decay within the earth.

Many diverse energy-related problems and challenges which relate to renewable energy are faced today. Some examples follow [27]:

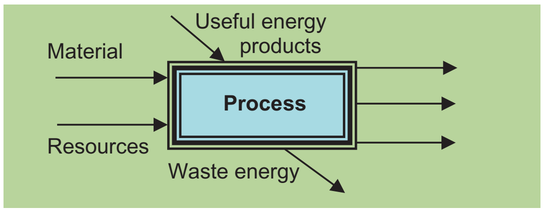


FIG. 4.10 Model of an industrial process.

TABLE 4.3 Energy and exergy values of various energy forms.

Source	Energy (J)	Exergy (J)	Exergy/energy ratio[a]
Water at 80°C	100	16	0.16
Steam at 120°C	100	24	0.24
Natural gas	100	99	0.99
Electricity/work	100	100	1.00

[a]*For heat, the exergy/energy ratio is the exergetic temperature factor* $\tau = (1 - T_0/T_s)$, *where* T_0 *is the absolute temperature of the environment and* T_s *is the absolute temperature of the stream. Calculations can be often simplified as Exergy = Energy × Exergy/energy ratio.*
Based on P.P.A.J. Van Schijndel, J. Den Boer, F.J.J.G. Janssen, G.D. Mrema, M.G. Mwaba, Exergy analysis as a tool for energy efficiency improvements in the Tanzanian and Zambian industries, in: International Conference on Engineering for Sustainable Development, July 27-29, University of Dar Es Salaam, Tanzania, 1998.

- Growing energy demand. The annual population growth rate is currently around 2% worldwide and higher in many countries. By 2050, the world population is expected to double and economic development is expected to continue, improving standards of living in many countries. Consequently, global demand for energy services is expected to increase by up to 10 times by 2050 and primary-energy demand by 1.5–3 times.
- Excessive dependence on specific energy forms. Society is extremely dependent on access to specific types of energy currencies. The effect of the multiday blackout of 2003 in Ontario and several northeastern US states illustrated the dependency on electricity supply, as access was lost or curtailed to computers, elevators, air conditioners, lights, and healthcare. Developed societies would come to a virtual standstill without energy resources.
- Energy-related environmental impacts. Continued degradation of the environment by people, most agree, will have a negative impact on the future, and energy processes lead to many environmental problems, including global climate change, acid precipitation, stratospheric ozone depletion, emissions of a wide range of pollutants including radioactive and toxic substances, and loss of forests and arable land.
- The dominance of nonsustainable and nonrenewable energy resources. Limited use is made today of renewable energy resources and corresponding technologies, even though such resources and technologies provide a potential solution to current and future energy-resource shortages. By considering engineering practicality, reliability, applicability, economics, and public acceptability, appropriate uses for sustainable and renewable energy resources can be found. Of course, financial and other resources should not always be dedicated to renewable energy resources, as excessively extravagant or impractical plans are often best avoided.
- Energy pricing does not reflect actual costs. Many energy-resource prices have increased over the last couple of decades, in part to account for environmental costs, yet many suggest that energy prices still do not reflect actual societal costs.
- The global disparity in energy use. Wealthy industrialized economies which contain approximately 25%–35% of the world's population use 65%–75% of the world's energy supply.

These and other energy-related issues need to be resolved if humanity and society are to develop sustainably in the future. Renewable energy resources appear to provide one component of an effective sustainable solution and can contribute over the long term to achieving sustainable solutions to today's energy problems.

4.3.11.1 Attributes, benefits, and drawbacks of renewables

The attributes of renewable energy technologies (e.g., modularity, flexibility, low operating costs) differ considerably from those for traditional, fossil fuel-based energy technologies (e.g., large capital investments, long implementation lead times, and operating cost uncertainties regarding future fuel costs). Renewable energy technologies can provide cost-effective and environmentally beneficial alternatives to conventional energy systems. Some of the benefits that make energy conversion systems based on renewable energy attractive follow:

- They are relatively independent of the cost of oil and other fossil fuels, which are projected to rise significantly over time. Thus, cost estimates can be made reliably for renewable energy systems and they can help reduce the depletion of the world's nonrenewable energy resources.
- Implementation is relatively straightforward.

- They normally do not cause excessive environmental degradation and so can help resolve environmental problems. Widespread use of renewable energy systems would certainly reduce pollution levels.
- They are often advantageous in developing countries. The market demand for renewable energy technologies in developing nations will likely grow as they seek a better standard of living.

Renewable energy resources have some characteristics that lead to problematic but often solvable technical and economic challenges:

- generally diffuse,
- not fully accessible,
- sometimes intermittent, and
- regionally variable.

The overall benefits of renewable energy technologies are often not well understood, leading to such technologies often being assessed as less cost-effective than traditional technologies. For renewable energy technologies to be assessed comprehensively, all of their benefits must be considered. For example, many renewable energy technologies can provide, with short lead times, small incremental capacity additions to existing energy systems. Such power generation units usually provide more flexibility in incremental supply than large devices like nuclear power stations.

4.3.11.2 The role of renewables in sustainable development

Renewable energy has an important role to play in meeting future energy needs in both rural and urban areas [28]. The development and utilization of renewable energy should be given a high priority, especially in the light of increased awareness of the adverse environmental impacts of fossil-based generation. The need for sustainable energy development is increasing rapidly in the world. Widespread use of renewable energy is important for achieving sustainability in the energy sectors in both developing and industrialized countries.

Renewable energy resources and technologies are a key component of sustainable development for three main reasons:

- They generally cause less environmental impact than other energy sources. The variety of renewable energy resources provides a flexible array of options for their use.
- They cannot be depleted. If used carefully in appropriate applications, renewable energy resources can provide a reliable and sustainable supply of energy almost indefinitely. In contrast, fossil fuel and uranium resources are diminished by extraction and consumption.
- They favor system decentralization and local solutions that are somewhat independent of the national network, thus enhancing the flexibility of the system and providing economic benefits to small isolated populations. Also, the small scale of the equipment often reduces the time required from initial design to operation, providing greater adaptability in responding to unpredictable growth and/or changes in energy demand.

Not all renewable energy resources are inherently clean in that they cause no burden on the environment in terms of waste emissions, resource extraction, or other environmental disruptions. Nevertheless, the use of renewable energy resources almost certainly can provide a cleaner and more sustainable energy system than increased controls on conventional energy systems.

To seize opportunities, countries should establish renewable energy markets and gradually develop experience with renewable technologies. The barriers and constraints to the diffusion of renewables should be removed. The legal, administrative, and financing infrastructure should be established to facilitate the planning and application of renewable energy projects. The government could play a useful role in promoting renewable energy technologies by initiating surveys and studies to establish their potential in both urban and rural areas. Fig. 4.11 shows the major considerations for developing renewable energy technologies.

As existing energy utilities often play a key role in determining the adoption and contribution of renewable energy technologies, the utility structure and the strategy for integrating renewables should be reviewed and studied. Utility regulations should be framed to reflect the varying costs over the networks, increase competitiveness, and facilitate access to independent renewable energy production. A major challenge for renewables is to get them into a reliable market at a price which is competitive with energy derived from fossil fuels, without disrupting local economies. Since the use of renewable energy often involves awareness of perceived needs and sometimes a change of lifestyle and design, it is essential to develop effective information exchange, education, and training programs. Knowledge of renewable energy technologies should be strengthened by establishing education and training programs. Energy research and development and

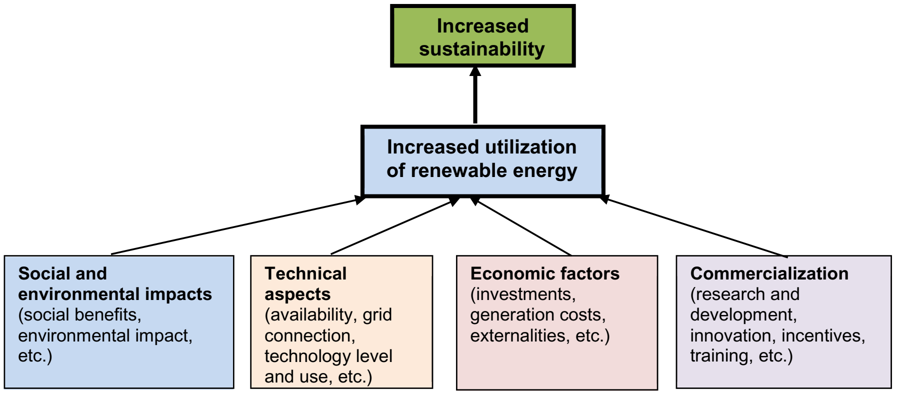


FIG. 4.11 Major considerations involved in the development of renewable energy technologies for sustainable development.

demonstration projects should be encouraged to improve information and raise public awareness. The technology transfer and development process should be institutionalized through international exchanges and networking.

To overcome obstacles in the initial implementation, programs should be designed to stimulate a renewable energy market so that options can be exploited by industries as soon as they become cost-effective. Financial incentives should be provided to reduce upfront investment commitments and to encourage design innovation.

4.3.11.3 Tools for environmental impact and sustainability

An energy system is normally designed to work under various conditions to meet different expectations (e.g., load, environment, and social expectations). Table 4.4 lists some available environmental tools and detailed descriptions of each tool follow [29, 30]:

- **Life Cycle Assessment (LCA):** LCA is an analytical tool used to assess the environmental burden of products at the various stages in a product's life cycle. In other words, LCA examines such products "from cradle-to-grave." The term "product" is used in this context to mean both physical goods as well as services. LCA can be applied to help design an energy system and its subsystems to meet sustainability criteria through every stage of the life cycle. LCA, as an environmental accounting tool, is very important.
- **Environmental Impact Assessment (EIA):** EIA is an environmental tool used in assessing the potential environmental impact of a proposed activity. The derived information can assist in deciding on whether or not the proposed activity will pose any adverse environmental impacts. The EIA process assesses the level of impacts and provides recommendations to minimize such impacts on the environment.
- **Ecological Footprints:** Ecological Footprints analysis is an accounting tool enabling the estimation of resource consumption and wastes assimilation requirements of a defined human population or economy in terms of corresponding productive land use.
- **Sustainable Process Index (SPI):** SPI is a measure of the sustainability of a process producing goods. The unit of measure is the square meter of land. It is calculated from the total land area required to supply raw materials, process energy (solar derived), provide infrastructure and production facilities, and disposal of wastes.
- **Material Flux Analysis (MFA):** MFA is a materials accounting tool that can be used to track the movement of elements of concern through a specified system boundary. The tool can be adapted further to perform a comparative study of alternatives for achieving environmentally sound options.

TABLE 4.4 Selected methods and tools for environmental assessment and improvement.

Risk tools	Environmental tools	Thermodynamic tools	Sustainability tools
Risk assessment	Environmental performance indicators	Exergy analysis	Life cycle assessment
	Environmental impact assessment	Material flux analysis	Sustainable process index
	Ecological footprints		Industrial ecology

- **Risk Assessment**: Risk Assessment can estimate the likelihood of potential impacts and the degree of uncertainty in both the impact and the likelihood it will occur. Once management has been informed about the level of risk involved in an activity, the decision of whether such a risk is acceptable can be subsequently made.
- **Exergy Analysis**: As discussed throughout this book, exergy is the quality of a flow of energy or matter that represents the useful part of the energy or matter. The conversion of energy in a process usually is driven by the consumption of energy quality. It is found that using the exergy concept to estimate the consumption of physical resources can improve the quality of the data necessary for LCA.

4.3.11.4 Ecologically and economically conscious process engineering

Numerous efforts have been made to develop and promote ecologically and economically sustainable engineering. When applying ecologically and economically sustainable engineering, industrial and ecological systems are treated as networks of energy flows.

Ecosystems convert sunlight to natural resources, while industrial systems convert natural resources to economic goods and services. Thus, all products and services are considered as transformed and stored forms of solar energy. An energy flow chart for a typical industrial system that includes ecological and economic inputs is shown in Fig. 4.12. The traditional economic analysis only accounts for economic inputs and outputs, since the industry does not pay money to nature for its products and services. LCA focuses mainly on the waste streams, and their impact, while systems ecology ignores wastes and their impacts. Fig. 4.12 can be used for assessing the economic and environmental viability of products and processes.

The thermodynamic approach to life cycle assessment and design accounts for economic and ecological inputs and services, and the impact of emissions. This approach is related to exergy. Exergy analysis is popular for improving the thermodynamic efficiency of industrial processes. However, it ignores ecological inputs and the impact of emissions. These shortcomings of exergy analysis have been overcome by combining it with life cycle impact assessment and emergy analysis. Emergy analysis is a popular approach for analyzing and modeling ecosystems. The resulting approach bridges systems ecology with systems engineering. Furthermore, applications of this approach to LCA and process design are being developed.

4.3.12 Exergy as a common sustainability quantifier for process factors

Exergy has several qualities that make it suitable as a common quantifier of the sustainability of a process [31]:

- Exergy is an extensive property whose value is uniquely determined by the parameters of both the system and the reference environment.
- If a flow undergoes any combination of work, heat, and chemical interactions with other systems, the change in its exergy expresses not only the *quantity* of the energetic exchanges but also the *quality*.
- Provided a chemical reference state is selected that is reflective of the actual typical chemical environment on Earth, the chemical portion of the exergy of a substance can be evaluated. The exergy of a substance such as a mineral ore or of fossil fuel is known when the composition and the thermodynamic conditions of the substance and the environment at

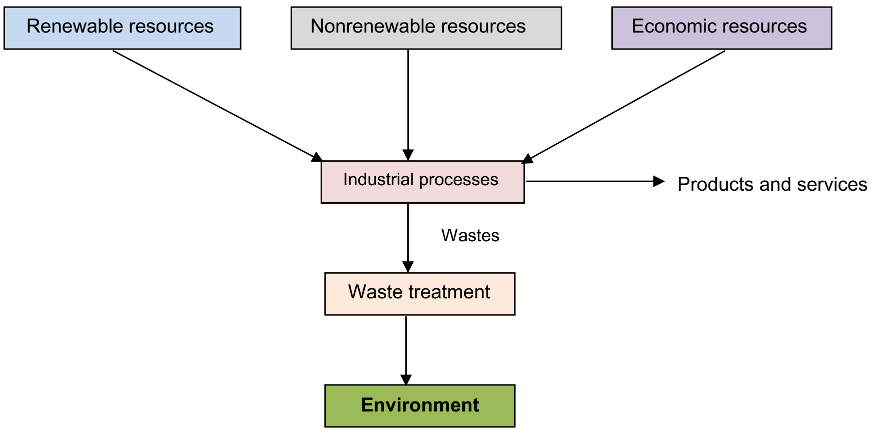


FIG. 4.12 Flow diagram for an industrial process that includes resource and economic inputs.

the extraction site are known. The chemical exergy of a substance is zero when it is in equilibrium with the environment, and increases as its state deviate from the environment state. For a mineral, for example, the exergy of the raw ore is either zero (if the ore is of the same composition as the environmental material) or higher if the ore is somewhat concentrated or purified.

- The *value* of a product of a process, expressed in terms of "resource use consumption," may be obtained by adding to the exergy of the original inputs all the contributions due to the different streams that were used in the process.
- If a process effluent stream is required to have no impact on the environment, the stream must be brought to a state of thermodynamic equilibrium with the reference state before being discharged into the environment. The minimum amount of work required to perform this task is by definition the exergy of the stream. For this reason, many suggest that the exergy of effluent is a correct measure of its potential environmental cost.

Some researchers [31] propose that an "invested exergy" value be attached to a processed product, defined as the sum of the cumulative exergy content of the product and the "recycling exergy" necessary to allow the process to have zero impact on the environment. They further suggest the following, for any process:

- A proper portion of the invested exergy plus the exergy of a stream under consideration can be assigned to the stream, thereby allowing the process to be "charged" with the physical and invested exergy of its effluents.
- If a feasible formulation exists to convert the remaining "nonenergetic externalities" (labor and capital) into exergetic terms, their equivalent input in any process could be added to the exergy and invested exergy of each stream. The exergy flow equivalent to labor can perhaps be estimated by assigning a resource value to the work hour, computed as the ratio of the yearly total exergetic input in a society or region to the total number of work hours generated in the same period. Similarly, the exergy flow equivalent to a capital flow can perhaps be estimated by assigning a resource value to the monetary unit, computed as the ratio between the yearly total exergetic input in a society or region and the total monetary circulation (perhaps in terms of gross domestic product, or total retail sales, or a different financial measure) in the same period.

In summary, we consider sustainable development here to involve four key factors (see Fig. 4.13): environmental, economic, social, and resource/energy. The connections in Fig. 4.13 illustrates that these factors are interrelated.

4.3.13 UN sustainable development goals

Adopted in 2015 by the United Nations, the 2030 Agenda for Sustainable Development aims to provide a shared plan for peace and prosperity for the Earth, countries, communities, and people that are supportable now and sustainable into the future [32, 33]. At its core are the 17 Sustainable Development Goals (SDGs), also known as Global Goals. These constitute a set of aims and, essentially, a call to attain them or shift toward them. This is directed at all countries, developing and developed, to work both individually and in partnership. Expanding on decades of work by the UN and many countries, the SDGs provide strategies that aim at enhancing health, education, and economic growth, while mitigating or removing deprivations and problems, including poverty, inequality, climate change and damage to forests and oceans.

Being both interdependent and broad-based, the SDG is as follows:

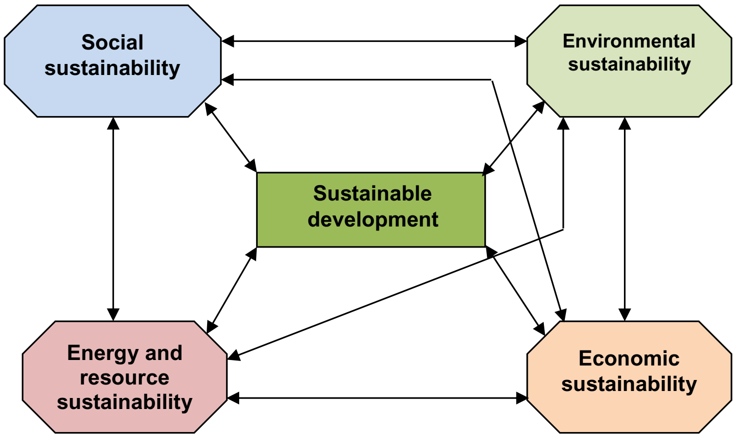


FIG. 4.13 Factors impacting sustainable development and their interdependences.

1. No Poverty
2. Zero Hunger
3. Good Health and Well-being
4. Quality Education
5. Gender Equality
6. Clean Water and Sanitation
7. Affordable and Clean Energy
8. Decent Work and Economic Growth
9. Industry, Innovation, and Infrastructure
10. Reducing Inequality
11. Sustainable Cities and Communities
12. Responsible Consumption and Production
13. Climate Action
14. Life Below Water
15. Life On Land
16. Peace, Justice, and Strong Institutions
17. Partnerships for the Goals

Each SDG has a list of targets (169 in all). These targets are measured with indicators, each target having 1 and 3 indicators, to measure and assess progress, and several tools exist to track progress toward the targets and the goals. It is intended that governments, businesses, civil society, and the general public use the goals for guidance in working together for a sustainable and improved future.

According to the United Nations Sustainable Development Goals platform (sustainabledevelopment.un.org/sdgs):

> *"The 17 Sustainable Development Goals (SDGs) are the world's best plan to build a better world for people and our planet by 2030. Adopted by all United Nations Member States in 2015, the SDGs are a call for action by all countries - poor, rich, and middle-income - to promote prosperity while protecting the environment. They recognize that ending poverty must go hand-in-hand with strategies that build economic growth and address a range of social needs including education, health, equality and job opportunities, while tackling climate change and working to preserve our ocean and forests."*

The 2030 Agenda for Sustainable Development and its SDGs, is premised on the following main guiding principles:

- *Aspiration*: It is necessary to go beyond business as usual and to develop transformational solutions.
- *Universality*: The goals apply in all countries and contexts.
- *Leaving No One Behind*: Success in achieving the SDGs requires the inclusion of everyone, including the most vulnerable and at-risk and the poorest.
- *Integration*: The achievement of any one goal is linked to the achievement of the others.

Exergy methods can help in achieving many of the SDGs and their targets, through the power exergy tools bring in assessing and improving efficiency, understanding and mitigating environmental impacts, and enhancing economics and the economic effectiveness and efficiency of human activities.

4.4 Illustrative example

The ideas discussed in this chapter are demonstrated for the process of electricity generation using a coal-fired steam power plant. The plant considered is the Nanticoke Generating Station, which is examined in detail in Section 11.6. Individual units of the station each have net electrical outputs of approximately 500 MW. A single unit (Fig. 4.14) consists of four main sections [5]:

- *Steam generators*: Pulverized-coal-fired natural circulation steam generators produce primary and reheat steam. Regenerative air preheaters are used and flue gas exits through chimneys.
- *Turbine generators and transformers*: Primary steam from the steam generators passes through turbine generators, which are connected to a transformer. Steam exhausted from the high-pressure cylinder is reheated and extraction steam from several points on the turbines preheats feed water.
- *Condensers*: Cooling water condenses the steam exhausted from the turbines.
- *Preheaters and pumps*: The temperature and pressure of the condensate are increased.

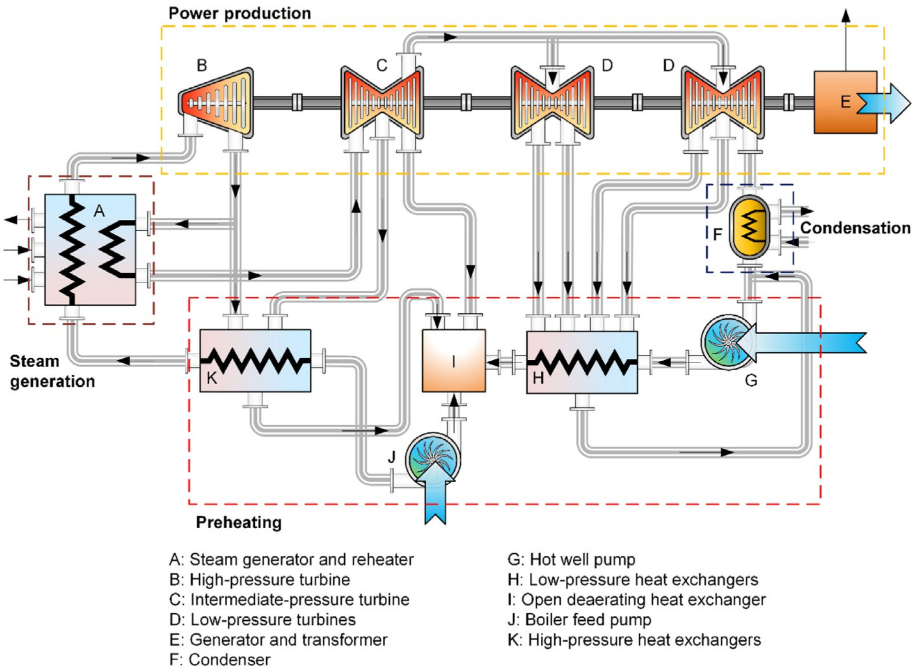


FIG. 4.14 Breakdown of a unit in the coal-fired electrical generating station into four main sections. The external inputs are coal and air, and the output is stack gas and solid waste for unit A. The external outputs for unit E are electricity and waste heat. Electricity is input to units G and J, and cooling water enters and exits unit F.

4.4.1 Implications regarding exergy and energy

Energy and exergy analyses of the station have been performed (see Section 11.6). Overall balances of exergy and energy for the station are illustrated in Fig. 4.15, where the rectangle in the center of each diagram represents the station. The main findings follow:

- For the overall plant, energy efficiency, defined as the ratio of net electrical energy output to coal energy input, is found to be about 37%, and the corresponding exergy efficiency 36%.
- In the steam generators, the energy and exergy efficiencies are evaluated, considering the increase in energy or exergy of the water as the product. The steam generators appear significantly more efficient on an energy basis (95%) than on an exergy basis (50%). Physically, this discrepancy implies that, although most of the input energy is transferred to the preheated water, the energy is degraded as it is transferred. Most of the exergy losses in the steam generators are associated with internal consumptions (mainly due to combustion and heat transfer).
- In the condensers, a large quantity of energy enters (about 775 MW for each unit), of which close to 100% is rejected; and a small quantity of exergy enters (about 54 MW for each unit), of which about 25% are rejected and 75% internally consumed.
- In other plant devices, energy losses are found to be small (about 10 MW total), and exergy losses are found to be moderately small (about 150 MW total). The exergy losses are almost completely associated with internal consumptions.

4.4.2 Implications regarding exergy and the environment

In this example of a conventional coal-fired electrical generating station, each of the relationships between exergy and environmental impact described in Section 4.2.4 is demonstrated:

- Waste exergy is emitted from the plant with waste stack gas, solid combustor wastes, and the waste heat released to the atmosphere and the lake from which condenser cooling water is obtained. The exergy of these emissions represents a potential to impact on the environment. Societal concern already exists regarding emissions of harmful chemical constituents in stack gases and thermal pollution in local water bodies of water, but the exergy-based insights into the environmental impact potential of these phenomena are not yet well understood or recognized.
- Coal, a finite resource, is degraded as it drives the electricity generation process. Although a degree of resource degradation cannot be avoided for any real process, increased exergy efficiency can reduce the amount of degradation, for the same services or products. In the extreme, if the process in the example were made thermodynamically ideal by

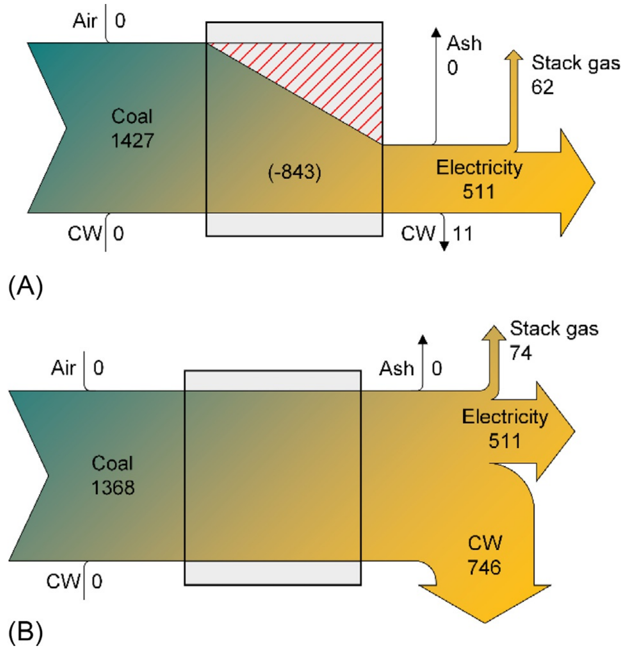


FIG. 4.15 Overall energy and exergy balances for the coal-fired electrical generating station. The rectangle in the center of each diagram represents the station. Widths of flow lines are proportional to the relative magnitudes of the represented quantities. CW denotes cooling water. (A) Exergy balance showing flow rates *(positive values)* and consumption rate *(negative value, denoted by hatched region)* of exergy (in MW). (B) Energy balance showing flow rates of energy (in MW).

increasing the exergy efficiency from 37% to 100%, coal use and the related emissions would each decrease by over 60%.

- Order destruction occurs during the exergy consuming conversion of coal to less ordered stack gases and solid wastes, and chaos creation occurs as wastes are emitted to the environment, allowing the products of combustion to move and interact without constraints throughout the environment.

4.4.3 Implications regarding exergy and sustainable development

The exergy-related implications discussed in this section assist in achieving sustainable development by providing insights into efficiency improvement and environmental impact reduction. These insights, combined with economics and other factors, can assist in improving the sustainability of (i) the electricity-generation process considered and (ii) the broader provision of electricity and electrical-related services in regions.

4.5 Sustainability assessment model for energy systems

Sustainability assessment is important, to understand when actions lead to progress and the degree of the progress. In this section, a sustainability assessment model for energy systems is described. This model contains eight dimensions, each of which has some indicators. The dimensions are energy, exergy, environment, economy, technology, social, education, and capacity factor. The dimensions and indicators are detailed in Fig. 4.16 for the model developed by Abu-Rayash and Dincer [34]. It is now presented as a case study here.

Four of the dimensions are presented below, in Eqs. (4.1)–(4.4).

The energy dimension has a significant effect on the sustainability assessment model and is expressed as follows:

$$Y_{ER} = \left(\eta \times W_\eta\right) + \left(Y_{Pr} \times W_{Pr}\right) \tag{4.1}$$

Generally, Y denotes the dimensionless value for an indicator, while W denotes the arithmetic weights assigned for the indicator. In Eq. (4.1), Y_{ER} denotes the total score of this dimension, which is calculated by the addition of the scores of the two indicators, η represents the nondimensional score of the efficiency of the energy system, W_η is the arithmetic

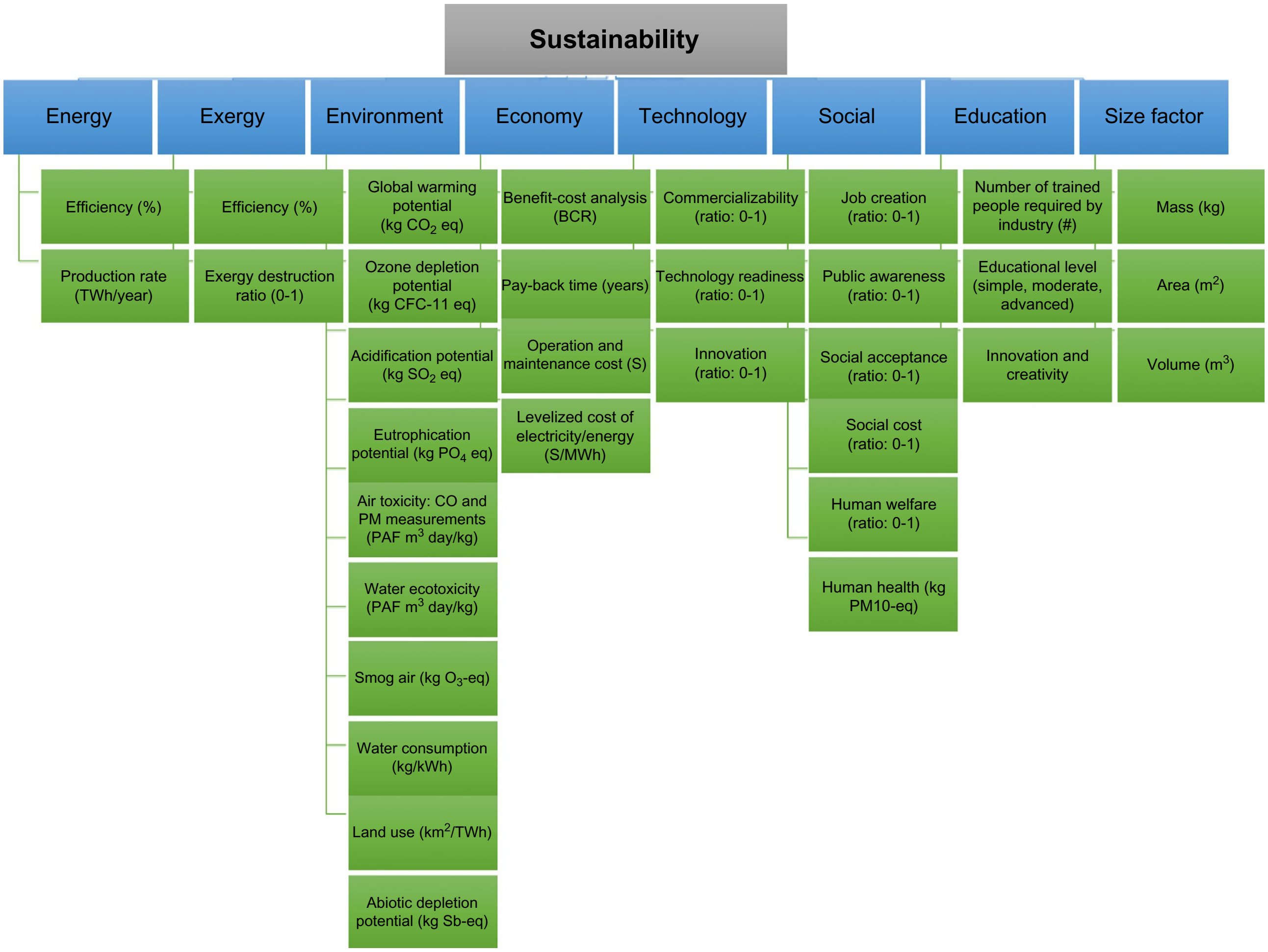


FIG. 4.16 A sustainability assessment model for energy systems, showing its eight dimensions (second row in blue) and indicators for each dimension (third and subsequent rows in green).

weight that is given for this indicator, Y_{Pr} denotes the nondimensional score of the productivity of the energy system and W_{Pr} is the weight associated with that indicator.

The environmental dimension contains many indicators to reflect the breadth of environmental factors, as follows:

$$Y_{ENV} = (Y_{GWP} \times W_{GWP}) + (Y_{ODP} \times W_{ODP}) + (Y_{AP} \times W_{AP}) + (Y_{EP} \times W_{EP}) + (Y_{AT} \times W_{AT}) + (Y_{WE} \times W_{WE}) + (Y_{SA} \times W_{SA}) + (Y_{WC} \times W_{WC}) + (Y_{LU} \times W_{LU}) + (Y_{ADP} \times W_{ADP}) \tag{4.2}$$

Here, ENV denotes environment, GWP global warming potential, ODP ozone depletion potential, AP acidification potential, EP eutrophication potential, AT air toxicity, WE water ecotoxicity, SA smog in the air, WC water consumption, LU land use, and ADP abiotic depletion potential.

The economic dimension covers three main indicators, as follows:

$$Y_{ECO} = (Y_{BCR} \times W_{BCR}) + (Y_{PBT} \times W_{PBT}) + (Y_{LCOE} \times W_{LCOE}) \tag{4.3}$$

where ECO represents economy, and W denotes the arithmetic weight associated with each indicator. Also, Y_{BCR}, Y_{PBT}, and Y_{LCOE} denote the nondimensional indicators of benefit-cost ratio, payback time, and the levelized cost of energy/electricity, respectively.

The weighted geometric mean calculation used for the aggregation method is as follows:

$$WGM_{(Y,W)} = \prod_{i=1}^{m} \left(Y_i^{W_i}\right) \tag{4.4}$$

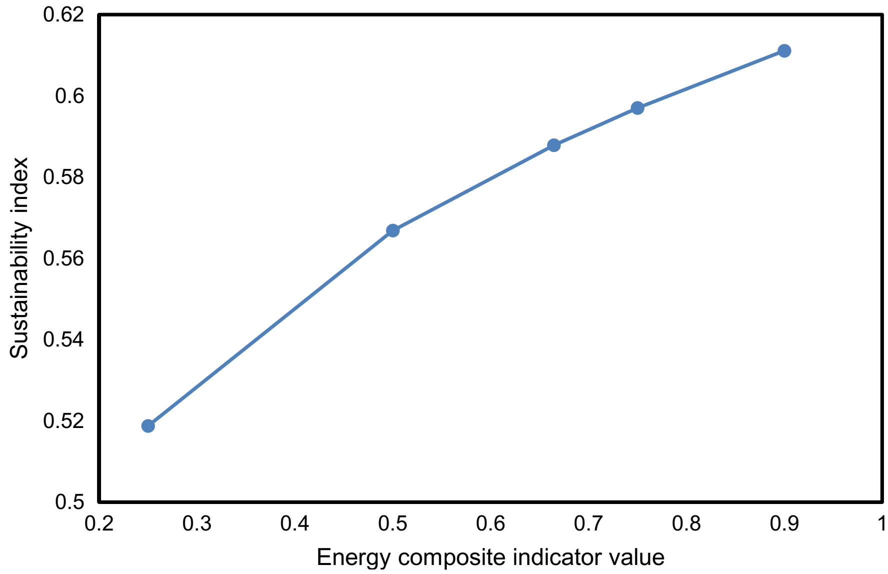


FIG. 4.17 Impact of energy composite indicator on the overall system sustainability index.

where Y_i denotes the nondimensional value of dimension i, W_i denotes the weight associated with dimension i, and m is the number of dimensions.

Each composite indicator is composed of a number of variables that are measured or evaluated. For example, the exergy indicator is a function of the exergy efficiency and the exergy destruction of the system. For this sample problem, a parametric analysis for the energy, environment, and economy composite indicators is conducted. The hierarchist method is used, as it is moderate and balanced, considering commonly held principles on technology and time. The hierarchist method is often considered as the default model while assessing sustainability, as opposed to the individualist or egalitarian methods.

Fig. 4.17 shows the final sustainability score of the energy system considered here as the energy composite indicator varies between 0.25 and 0.90.

The relationship between the environment composite indicator and the sustainability index is illustrated in Fig. 4.18. Note that this composite indicator is assigned a higher weight based on the panel weighting method. Besides, this composite indicator factors in global warming potential (GWP), ozone depletion potential (ODP), and many other variables highlighted in Fig. 4.18.

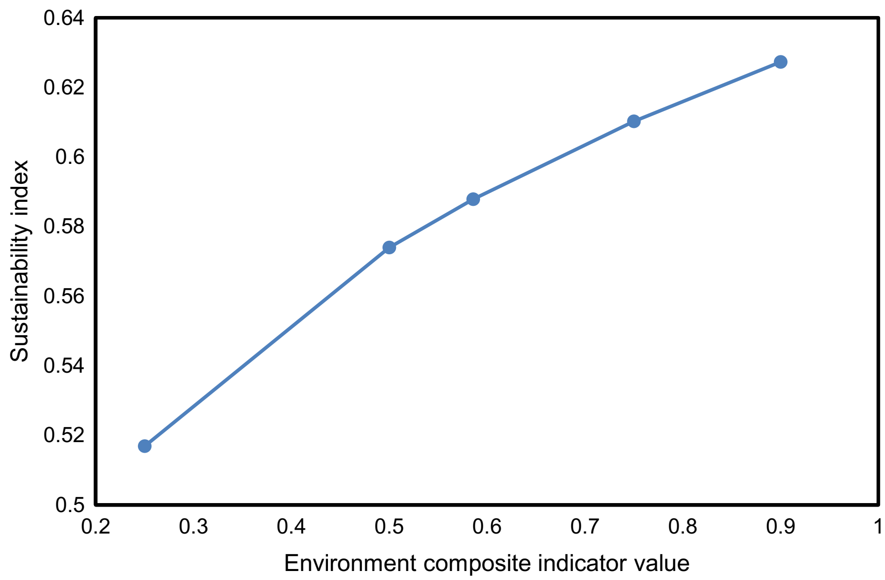


FIG. 4.18 Impact of environment composite indicator on the overall system sustainability index.

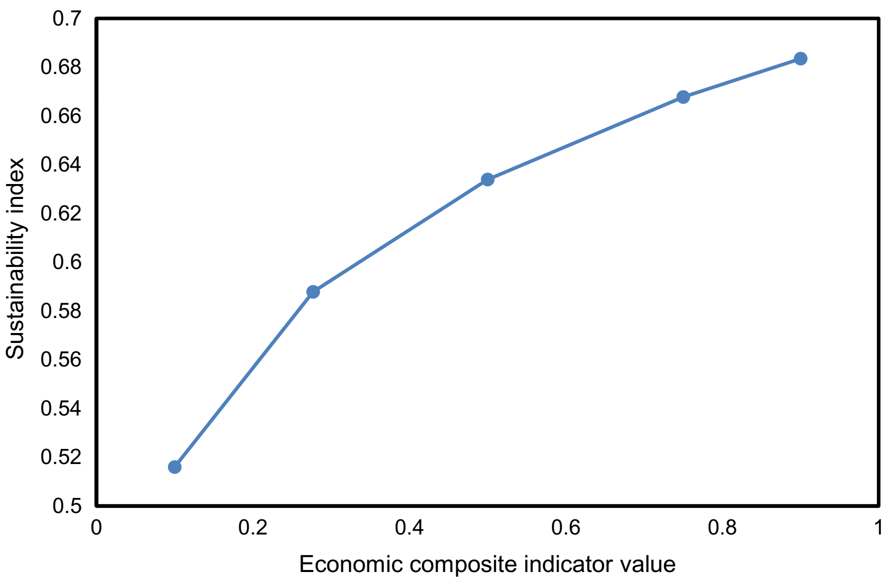


FIG. 4.19 Impact of economic composite indicator on the overall system sustainability index.

Lastly, the impact of the economy composite indicator on the overall sustainability index is presented in Fig. 4.19. This composite indicator factors in payback time, system operation and maintenance cost, levelized cost of electricity along with a cost-benefit analysis.

4.6 Closing remarks

This chapter discusses the relations between exergy and energy, environmental impact, and sustainable development. Three main relations between exergy and environmental impact are extensively discussed in terms of order destruction and chaos creation, resource degradation, and waste-exergy emissions. The potential usefulness of exergy analysis in addressing and solving energy-related sustainable development and environmental problems is shown to be substantial. Besides, thermodynamic principles, particularly the concepts encompassing exergy, are shown to have a significant role to play in evaluating energy and environmental technologies. Some key points, which will likely be useful to scientists and engineers as well as decision and policymakers, can be drawn from this chapter:

- Moving toward sustainable development requires that environmental problems be resolved. These problems cover a range of pollutants, hazards, and types of ecosystem degradation, and extend over various geographical areas. Some of the most significant environmental problems are acid precipitation, stratospheric ozone depletion, and global climate change, with the latter being potentially the most significant.
- Sustainable development requires a sustainable supply of energy resources that, in the long-term, is sustainably available at a reasonable cost and can be utilized for all required tasks without causing negative societal impacts. Energy sources such as sunlight, wind, and falling water are generally considered renewable and, therefore, sustainable over the relatively longer term.
- Assessments of the sustainability of processes and systems, and efforts to improve sustainability, should be based in part upon thermodynamic principles, especially the insights revealed through exergy analysis.
- For societies to attain or try to attain sustainable development, effort should be devoted to developing renewable energy resources and technologies. Renewable energy technologies can provide environmentally responsible and sustainable alternatives to conventional energy systems, as well as more flexibility and decentralization.
- To realize the energy, exergy, economic, and environmental benefits of renewable energy sources, an integrated set of activities should be conducted including research and development, technology assessment, standards development, and technology transfer. These can be aimed at improving efficiency, facilitating the substitution of renewable energy, and other environmentally benign energy currencies for more harmful ones, and improving the performance characteristics of renewable-energy technologies.

Through the example in Section 4.4, the authors have attempted to provide some practical illustrations of the more abstract concepts discussed in this chapter, particularly by highlighting the importance of understanding and considering the relations of exergy to energy and environmental impact, especially for sustainable development challenges and problems. Such an enhanced understanding of sustainability and environmental issues relating to energy-resource use is needed both to allow the problems to be better addressed and to help develop solutions that are beneficial for the economy and society.

4.7 Problems

4.1 What is the relationship between energy efficiency, environment, and sustainability?
4.2 What is the relationship between the use of renewable energy sources, environment, and sustainability?
4.3 What is the relationship between exergy, environment, and sustainable development?
4.4 Name two policies that promote the better use of energy so as to support sustainable development and explain how these policies can relate to exergy.
4.5 Name several major environmental concerns and explain how the exergy concept can help reduce or mitigate them.
4.6 Is there any way of eliminating emissions of gases that cause global warming while using fossil fuels?
4.7 Describe the concept of "greenhouse gas emissions trading" and discuss its implications.
4.8 Identify ten potential solutions to environmental problems. Identify and describe three of the most effective solutions.
4.9 List the barriers to the development of renewable and advanced energy technologies. Discuss how these barriers can be overcome.
4.10 Is it possible to achieve sustainable development as defined by The Brundtland Commission? Discuss if this definition is realistic.
4.11 Does a process with a high exergy efficiency necessarily cause little environmental impact and lead to a high level of sustainability? Does a process with a low exergy efficiency necessarily cause much environmental impact and lead to a low level of sustainability? Discuss with examples.
4.12 What is industrial ecology and how is it, or can it be, related to exergy and sustainable development?
4.13 What is life cycle assessment and how is it, or can it be, related to environment and sustainable development?
4.14 What is exergetic life cycle assessment and how is it, or can it be, related to environment and sustainable development?
4.15 Identify a fossil fuel-fired electrical power station in your area and conduct a general exergy analysis using actual plant data following the illustrative example given in Section 4.4. Discuss the results.
4.16 Identify a fossil fuel-fired electrical power station in your area and determine the number of emissions it generated in the last year. Determine the number of cars that emit the same amount of emissions annually.
4.17 Identify which of the Sustainable Development Goals relate to exergy concepts or methods, and describe the relations.
4.18 Explain how exergy methods can be used to support and/or achieve each of the Sustainable Development Goals that relate to exergy concepts or methods.
4.19 Write an essay on how exergy is closely linked to the economic developments of countries. Is there a way to differentiate the concept for developed and developing countries? Explain what parameter plays a key role.
4.20 Relate exergy to the technological development and develop an integrated model.

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