ENVIRONMENT, ECOLOGY AND EXERGY

ENHANCED APPROACHES TO ENVIRONMENTAL AND ECOLOGICAL MANAGEMENT

ENVIRONMENTAL SCIENCE, ENGINEERING AND TECHNOLOGY

Marc A. Rosen
Mohsen Darabi

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MARC A. ROSEN
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To Allison, Cassandra, Ryan and Amanda, in hopes of a cleaner world

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PREFACE

Growing concerns about the environmental and ecological implications of industrial and other systems, as well as the impact of energy resource utilization, are fostering increasing interest in environmental and ecological protection. Such understanding is crucial to advancing the quest for a cleaner environment and sustainability. New approaches to ecology and the environment that provide an engineering perspective and a scientific basis to activities are of particular interest. The integration of the thermodynamic quantity exergy with the environment and ecology provides a novel approach that offers significant potential to improve environmental and ecological management.

In the analysis of environmental impact and improvement of ecological systems, techniques can be used which combine scientific disciplines (mainly thermodynamics) with environmental and ecological disciplines. In such analyses, assessments usually consider thermodynamics via energy quantities. Many researchers recommend, however, that ecological and environmental factors are better assessed using the thermodynamic quantity exergy. One rationale for this statement is that exergy, but not energy, can provide, or form the basis of, a measure of the potential for ecological and environmental impact.

Several exergy-based ecological and environmental methodologies exist (e.g., environomics, exergy-based life cycle analysis and exergy-based ecological indicators). A brief summary is presented here of existing analysis techniques which integrate exergy with ecological and environmental factors. One approach, for instance, identifies as important the exergy emitted from smokestacks and assesses the potential impact of that exergy using exergy-based tolerance measures. The goals of most such analysis techniques include improving our understanding of the impact on ecological systems and the environment of processes and the determination of appropriate ecological and environmental improvement measures. In this book, we focus on the relations linking ecological and environmental impacts and indicators with exergy.

Several examples are considered, including electricity generation, cogeneration, transportation and biofuels processing, illustrating the insights provided by integrating thermodynamics into ecological and environmental management. Thermodynamic, ecological and environmental data for various devices and systems are examined, and show that correlations exist between exergy and environmental and ecological parameters. The existence of such correlations suggests that aspects of exergy factor into environmental improvement and ecological management.

This book has four parts. In the first, introductory and background material is presented, including an explanation of the motivation for the book, a brief review of the disparate but relevant topics that it combines (e.g., energy, environment, society and sustainability), an introduction to exergy, the environment and ecology, and a history of exergy-based environmental and ecological methods.

In the second part, key concepts and methods are described. This includes exergy analysis, as well as suitable reference environments for environmental and ecological assessments. Furthermore, exergy and its relations to the environment and ecology are examined, and correlations between exergy and other indicators of environmental impact are presented. Finally, exergy-based environmental and ecological methods are identified and described, and extensions of the relations between exergy, environment and ecology to economics are examined.

Various applications are presented in third part of the book. These range from applications of exergy analysis on its own, to applications of the linkages between exergy and both the environment and ecology. Some specific applications are considered in greater depth, including assessments using exergy of Earth's resources, polluted materials, carbon dioxide emissions allocations for cogeneration and the environmental impact of aerospace operations. This section closes by describing environmental planning with exergy.

The final part of the book examines numerous case studies to provide detailed examinations of the integration of exergy with environmental and ecological management, in order to clarify the importance and potential benefits of such an approach. The case studies considered span a range of fields including energy conversion (e.g., coal-fired and nuclear electricity generation, and cogeneration), fuels processing (e.g., biofuels processing and hydrogen production, smokestack operations, and transportation (e.g., automotive operations). A broader case study is also included, which examines exergy-guided environmental management for countries, regions and sectors. The case studies provide useful information for practical applications. Finally, closing remarks are provided along with speculations on future directions and, to help direct the curious and interested reader to appropriate resources, an extensive list of references is provided.

This book is intended for use by graduate and advanced undergraduate students in various disciplines ranging from environmental engineering, environmental studies, ecology and environmental science, to general engineering and science as well as energy studies. Additionally, the book is intended to provide a useful reference for practicing environmental and ecological experts, engineers and scientists. Given the fact that the field of exergy, environment and ecology is in many ways in its infancy, this book is in part oriented towards research, permitting it to provide practical features often not included in purely academic books. The coverage is broad, and the amount of information presented, if studied in depth, can be sufficient for more than one course. This book is expected to be of importance to students, engineers, and scientists, as well as those who wish to know more about the growing area of this enhanced approach to environmental and ecological management.

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NOTATION

ROMAN LETTERS

BOD	biochemical oxygen demand
c	unit economic value; unit cost
c_E	unit economic value of electrical product of cogeneration
c_p	specific heat at constant pressure
c_Q	unit economic value of thermal product of cogeneration
C	total CO_2 emissions from cogeneration; contaminant concentration
C_E	CO_2 emissions associated with electrical energy produced via cogeneration
C_Q	CO_2 emissions associated with thermal energy produced via cogeneration
CExC	cumulative exergy consumption
CNEx	net exergy consumption
COP	coefficient of performance
D_p	depletion factor
E	energy; net electrical energy output from cogeneration
ex	specific exergy
Ex	exergy
Ex_E	net output of electrical exergy from cogeneration
Ex_{FE}	fuel exergy consumption for generating electricity via cogeneration
Ex_{FQ}	fuel exergy consumption for producing thermal exergy via cogeneration
Ex_Q	thermal exergy; net output of thermal exergy from cogeneration
Ex_P	product exergy
f	fraction
f_E	fraction of cogeneration emissions allocated to electrical product
f_Q	fraction of cogeneration emissions allocated to thermal product
F	total primary fuel energy consumed in cogeneration
F_E	fuel consumption attributed to electricity generation
F_Q	fuel consumption attributed to production of thermal energy
g	specific Gibbs function
G	Gibbs function
h	specific enthalpy
I	exergy consumption
I_r	renewability indicator

m	mass
M	molecular weight
n	number of moles
P	pressure
P_o	reference-environment pressure
P_{oo}	partial pressure of component in reference state
Q	heat; net output of thermal energy from cogeneration
R	universal gas constant (8.314 J/mol/K)
s	specific entropy
S	entropy
SI	sustainability index
T	temperature
T_o	reference-environment temperature
V	volume
W	work
W_P	produced work
W_R	restoration work
x	mole fraction
X	variable representing a reference-environment property
Y	variable representing either energy or exergy

Greek Letters

γ	activity coefficient
η	energy efficiency
η_b	energy efficiency of independent device (e.g., boiler) for thermal energy
η_E	energy efficiency of generating electrical energy via cogeneration
η_{gen}	generator efficiency
η_{isen}	turbine isentropic efficiency
η_{mech}	turbine mechanical efficiency
η_{pp}	energy efficiency of independent device for electrical energy
η_Q	energy efficiency of producing thermal energy via cogeneration
η_{tran}	transformer efficiency
μ	chemical potential
ν	stoichiometric coefficient
Π	entropy production
ρ	density
σ	sensitivity
τ	exergetic temperature factor
φ	CO_2 emission coefficient for a fuel
ψ	exergy efficiency
ψ_E	exergy efficiency of generating electricity via cogeneration
ψ_Q	exergy efficiency of producing thermal energy product via cogeneration

SUBSCRIPTS

C	contaminant
C,1	polluted water
C,2	cleaned water
i	stream component
j	sector j; *j*th reactant substance
k	chemical constituent; *k*th product substance; exiting stream
min	minimum
o	reference-environment state
p	product; process
ph	physical component
w	waste treatment

SUPERSCRIPTS

•	rate per unit time
ch	chemical

ACRONYMS

AP	acidification potential
CCME	Canadian Council of Ministers of the Environment
CD	conventional diesel
CG	conventional gasoline
CGV	conventional gasoline vehicle
CHP	combined heat and power
CIDI	compression ignition direct injection
CML	Center of Environmental Science of Leiden University
CNG	compressed natural gas
CNGV	compressed natural gas vehicle
CRFG2	California Phase 2 reformulated gasoline
E85	85% ethanol and 15% gasoline fuel blend by volume
EEA	extended exergy accounting (analysis)
EP	eutrophication potential
EPC	environmental pollution cost
EV	dedicated electric vehicle
ExLCA	exergetic life cycle assessment
EXCEM	exergy, cost, energy and mass
FFV	flexible-fuel vehicle
FRFG2	Federal Phase 2 reformulated gasoline
GC	grid-connected
GHG	greenhouse gas
GI	grid-independent
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Transportation
GWP	global warming potential
HEV	hybrid electric vehicle
IC	internal combustion
ICE	internal combustion engine
ISO	International Standards of Organization
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LPG	liquefied petroleum gas

MTBE	methyl tertiary butyl ether
M85	85% methanol and 15% gasoline fuel blend by volume
NRR	non-renewable resource
ODP	ozone depletion potential
PEM	polymer electrolyte membrane
POI	point of impingement
RPC	removal pollution cost
SI	spark ignition
SIDI	spark ignition direct injection
SPECO	specific exergy costing
TES	thermal energy storage
VMT	vehicle mile traveled

GLOSSARY

Descriptions are presented of the terminology related to exergy-based environment and ecology methods, and to exergy. Most of this terminology has only recently been adopted and is still evolving. The glossary is based in part on previously developed broader glossaries (Kotas et al., 1987; Kotas, 1995; Kestin, 1980; Dincer and Rosen, 2010; Tsatsaronis, 2007b).

EXERGY-BASED ENVIRONMENT AND ECOLOGY TERMINOLOGY

Acidification potential. Potential of acidifying pollutants, usually anthropogenic, to acidify natural or artificial substances (e.g., soil, groundwater, surface waters, biological organisms, ecosystems, building materials) after deposition on them.

Carbon exergy tax. A tax on carbon use or emissions intended to promote the efficient use of exergy resources.

Cumulative exergy consumption. An environmental impact measure based on the exergy used, in raw and other materials, to generate a product.

Depletion factor. The fraction of the input energy for a process that is dissipated rather than converted to useful products or services, evaluated as the ratio of exergy destruction to input exergy.

Dissipative function. A function that does not yield a useful output or productive, but instead is dissipative in nature.

Ecological supply chain. The supply chain for an ecological system.

Emergy. An extension of thermoeconomics aimed at understanding the environmental implications of an energy system, including the biosphere.

Environmental pollution cost. Environmental costs of pollutant based on quantitative and qualitative evaluations of the cost to correct or compensate for environmental damage, and/or to prevent a harmful emission.

Eutrophication potential. Potential of macronutrient emissions, usually anthropogenic, to cause eutrophication.

EXCEM analysis. An analysis tool that evaluates and tracks flows of exergy, cost, energy and mass, so as to attain a comprehensive and multi-faceted assessment of performance (technical, environmental, etc.).

Exergetic life cycle assessment. An exergy-based analysis tool for investigating and reducing the environmental impacts of a system or process or product, accounting for its full life cycle, which extends life cycle assessment by accounting for the exergy utilization and destruction during the life cycle.

Exergy tax. A tax on exergy to promote the efficient use of exergy resources, improved designs, and reduced resource utilization and environmental damage.

Exergoecology. An environmental application of exergy involving its utilization in evaluating natural fluxes and resources as well as ecosystems.

Exergoenvironmental analysis. The application of exergy for evaluating environmental impacts.

Extended exergy accounting. An assessment method of a complex system that involves determining the cost of a commodity based on its resource-base equivalent value as opposed to its monetary cost.

Global warming potential. Potential of emissions, usually anthropogenic, to increase the Earth's surface temperature and thus contribute to climate change.

Life cycle assessment. An analysis tool for investigating and reducing the environmental impacts of a system or process or product, accounting for its full life cycle (i.e., from cradle to grave).

Net exergy consumption. The net quantity of exergy consumed in generating a product, including all steps from the extraction of raw materials through to manufacturing.

Ozone depletion potential. Potential of emissions, usually anthropogenic, to deplete ozone in the stratospheric ozone layer.

Physical hydronomics. A discipline for assessing environmental costs related to water.

Rebound effect. An effect that partially or fully offsets the expected reduction in energy use associated with an increase in efficiency by inadvertently causing the use of the products or services to increase.

Removal pollution cost. Cost of removing one or more pollutants from a waste stream prior to discharge to the environment.

Renewability indicator. A measure of renewability that accounts for relevant factors in terms of exergy and integrates them in a unified manner.

ENERGY TERMINOLOGY

Heat. A form of energy transfer between systems due to a temperature difference.

State. The condition of a system specified by the values of its properties.

System. A quantity of matter or any region of space (also thermodynamic system).

Work. A form of energy transfer including such forms as mechanical, electrical, magnetic.

EXERGY TERMINOLOGY

Chemical exergy. The maximum work obtainable from a substance when it is brought from the environmental state to complete equilibrium with the reference environment by means of processes involving interaction only with the environment.

Energy analysis. A technique for analyzing processes based solely on energy and the first law of thermodynamics.

Energy efficiency. An efficiency determined using ratios of energy.

Entropy. A measure of disorder, which always increases for the universe.

Entropy production. The entropy increase of an isolated system consisting of all systems involved in the process.

Exergoeconomics. A techno-economic method for assessing and designing systems and processes that combines economics with exergy parameters, including the exergy costing.

Exergy (general). The maximum work potential of a system (non-flow exergy) or flow of matter, or a heat interaction, in relation to the reference environment as the datum state.

Exergy (matter-based). The maximum amount of shaft work obtainable when a steady stream of matter is brought from its initial state to the state of the reference environment by means of processes involving interactions only with the latter.

Exergy analysis. A technique based on the second law of thermodynamics in which process performance is assessed by examining exergy quantities and balances.

Exergy consumption. The exergy consumed or destroyed during a process due to irreversibilities within the system boundaries.

Exergy loss. The exergy lost due to the combination of exergy consumption due to irreversibilities and waste exergy emissions.

Exergy efficiency. A second-law efficiency determined using ratios of exergy.

External irreversibility. The portion of the total irreversibility for a system and its surroundings occurring outside the system boundary.

Internal irreversibility. The portion of the total irreversibility for a system and its surroundings occurring within the system boundary.

Irreversibility. An effect which makes a process non-ideal or irreversible.

Irreversible process. A process in which both the system and its surroundings cannot be returned to their initial state(s) through a subsequent reversible process.

Physical exergy. The maximum amount of shaft work obtainable from a substance when it is brought from its initial state to the environmental state by means of physical processes involving interaction only with the environment.

Reference environment. An idealization of the natural environment characterized by a state of equilibrium (absence of differences in pressure, temperature, chemical potential, kinetic energy and potential energy), with respect to which exergy is evaluated.

Reversible process. A process in which both the system and its surroundings can be returned to their initial state(s) with no observable effects.

Thermal exergy. The exergy associated with a heat interaction, i.e., the maximum amount of shaft work obtainable from a given heat interaction using the environment as a thermal energy reservoir.

Thermoeconomics. See exergoeconomics.

PART I:
INTRODUCTION AND BACKGROUND

Chapter 1

MOTIVATION

OVERVIEW

The motivation is described for this book on environmental and ecological management and its enhanced approach based on the integration of exergy with the environment and ecology. Founded on the first and second laws of thermodynamics, the integrated approach offers a means to improve the environmental characteristics of processes and systems. The motivation is based in part on the need to understand better these environmental and ecological implications to support environmental protection and sustainability. Thermodynamic theories of environmental and ecological impact proposed in the past have not achieved widespread acceptance, and this book partly aims to improve acceptance of this idea through its exergy-based approach.

This is a book on environmental and ecological management that describes an enhanced approach based on the integration of environmental and ecological disciplines with exergy. The motivation for such a book likely requires an explanation. This chapter introduces the book and explains its motivation.

1.1. ENERGY, ECOLOGY AND THE ENVIRONMENT

Interest in energy has been increasing for several decades for various reasons, including recognition of the impact of energy on the environment, living standards and economic development, and their linkages. In addition, concerns have been growing regarding:

- the environmental and ecological implications of energy systems,
- the sustainability of energy systems and the society's they serve,
- the adequacy of energy supplies for a planet with an increasing population and rapidly expanding energy use, particularly in developing countries, and
- the security and affordability of energy resources.

Economics has historically been central to the analysis and design of energy systems, which encompass technologies and processes for energy conversion, distribution, storage and utilization. Design and optimization methods for such technologies often focus on technical and economic areas.

In recent decades, environmental and ecological impacts have become important considerations in the analysis and design of technologies. Analysis, design and optimization activities now tend to utilize techniques that combine technical disciplines, economics and other factors with environmental and ecological disciplines.

Understanding and mitigating the environmental and ecological impacts of energy systems is crucial to advancing society's quest for overall sustainability, and to the proper development and beneficial application of energy technologies and systems, especially those which are new and advanced.

New approaches to environmental and ecological management that facilitate more environmentally and ecologically benign uses of energy resources of particular interest. One such approach is based on the integration of exergy with the environment and ecology. This novel approach offers significant potential to improve our energy systems and their sustainability, and that is why it is the focus of this book.

Although the environmental and ecological impacts of systems are important factors in decisions related to their adoption and development, it is pointed out that the merit of a system or process is usually based on a range of factors. Conventional parameters normally take into account not only environmental and ecological protection, but also technical performance, efficiency, health, safety, economics, resource scarcity and societal acceptance. The merit of a system or process is best evaluated with methodologies that take into account holistically the above factors and others. A systems viewpoint is usually advantageous for evaluating and comparing energy technologies and operations while accounting for all relevant factors, as such a viewpoint provides context and comprehensiveness.

1.2. WHY A BOOK ON EXERGY, ECOLOGY AND THE ENVIRONMENT?

Although the merit of a system or process is based on numerous factors, economics remains central. The environment and ecology are almost always not priorities in the analysis and design of systems and technologies, although they are receiving increasing recognition.

Analysis, design and optimization activities for such technologies are thus increasingly utilizing techniques that combine technical disciplines like thermodynamics with the environment and ecology.

Nonetheless, many experts have called for changes in the manner in which the environment and ecological systems are managed, in part due to the potentially disruptive global effects associated with issues like climate change. The environmental fears kindled by this issue combined with the energy concerns described above leave many people feeling that present approaches to environmental and ecological management may not be adequate.

A desire thus exists for new and advanced ways of addressing environmental and ecological management, which can maintain or improve living standards and prosperity, while maintaining environmental and ecological health. This book aims to satisfy this desire by elucidating an enhanced approach to environmental and ecological management that integrates the environment and ecology with the thermodynamic quantity exergy.

1.3. DEFINING ECOLOGY AND THE ENVIRONMENT

We consider throughout this book both the environment and ecology, which are distinct albeit related terms. To provide clarity, these terms and related concepts are explained and contrasted in this section.

1.3.1. Ecology

Ecology is a scientific discipline, usually considered a subset of biology, which examines ecosystems and relations between living organisms and the natural environment. Living organisms can be characterized by such factors as abundance, distribution, composition and state, as well as changes in these factors. Ecology provides an understanding of life processes and adaptations, the development and health of ecosystems, the amount and distribution of biodiversity, and the utilization of materials and energy by communities. Ecology is applied in many areas, including natural resource management, conservation, wetland management, agriculture, forestry, fisheries, urban planning, health, economics and engineering.

Ecosystem

Ecosystems are hierarchical natural systems that have parts like species that aggregate into higher orders of complexity in integrated communities. Ecosystems can be characterized by their biodiversity, considered from varying perspectives (e.g., genes, species). Ecosystems sustain various life-supporting functions on Earth (climate regulation, soil formation, water filtration, food growth, etc.). Biophysical feedback mechanisms exist in ecosystems between biotic (living) and abiotic (nonliving) components of the Earth. These feedback mechanisms regulate and sustain processes that are not just local, but also regional global and in extent (e.g., continental climate systems, biogeochemical cycles).

1.3.2. Environment

The environment generally refers to all living and non-living things that occur naturally on Earth, i.e., the natural environment.

The environment can also refer, in a more restricted sense, to the surroundings of an object. This is typical in disciplines such as thermodynamics.

Environmental Impact

Environmental impact is the effect of an action or event on the natural environment. The effect can positive or negative, although it usually is latter type that receive attention. Environmental impact can be viewed at a given time, or over the life cycle – from the harvesting of all required resources through to their ultimate disposal) of a system, product or process. Environmental impact includes direct effects, as well as indirect effects (e.g., use of goods and services, production of materials and equipment, additional land use for manufacturing and industrial operations, mining and harvesting of resources). Indirect environmental effects sometimes exceed direct effects.

Environmental Science

Environmental science is the study of the environment and environmental systems, as well as the interactions among the physical, chemical and biological components of the environment. Environmental science provides an understanding of natural resources and planetary processes like global climate change, as well as the environmental impact of industrial and engineered systems, pollution and energy systems. Environmental science is applied in various areas including predicting the effects of pollution and the efficacy of control and mitigation options, and natural resource management.

Environmental science is sometimes considered to encompass ecology, and relates to environmental engineering, which focuses on design and technology for environmental quality, as well as environmental studies, which focuses on human relationships, perceptions and policies towards the environment. But ecology differs from environmental science, and ecosystems differ from the environment.

Environmental Engineering

Environmental engineering is the application of engineering and scientific principles directly to the environment (air, water, land) or to systems and processes that interact with the environment. Environmental engineering includes safeguarding of the natural environment, the provision of healthy water, air, and land for humans and other organisms, the remediation of polluted sites, management and disposal of wastes (e.g., wastewater) and hazardous wastes, air pollution control, recycling, radiation protection, industrial hygiene, sustainability, and the effect of all of these on the public welfare. Environmental engineering also encompasses the development and design of technologies, systems and processes to improve or safeguard the quality of the environment directly or as part of other engineering systems. Local, regional and global environmental issues (e.g., climate change, acid precipitation, ozone depletion, pollution) as well as their causes and sources are often the focus of environmental engineering. Environmental engineering sometimes involves developing, or providing information for the development of, regulations, codes and policies.

Environmental Impact Assessment

An environmental impact assessment is an evaluation of the potential impacts – negative or positive – of a project on the natural environment including ecosystems, accounting for technical, economic and social factors. An environmental impact assessment includes identification, prediction and evaluation of environmental effects and mitigation options.

The scope of an environmental impact assessment can range from local to global, thereby encompassing factors ranging from local aesthetics to threats to species and resources. The scope of an environmental impact assessment can also range from an examination of specific steps to a full life cycle, accounting in the latter case for activities involved in the various stages of a system, process or product (e.g., extraction of raw material and energy resources for the product or system or process and for ancillary equipment, manufacturing and production, product utilization, disposal of the product and ancillary equipment).

Environmental impact assessments are usually used to inform decision making on project proposals. Given uncertainties regarding data and effects as well as individual interpretations of impacts and preferences, environmental impact assessments can be controversial.

1.4. THERMODYNAMICS, EXERGY, ECOLOGY AND THE ENVIRONMENT

Many authors suggest that the first and second laws of thermodynamics have significant implications for environmental and ecological quality and impact.

Assessments of environmental and ecological impact for energy and other systems normally consider energy quantities.

Many researchers note that the thermodynamic quantity exergy, which stems from the second law of thermodynamics, provides a measure of the potential for environmental or ecological impact, while energy does not. Consequently, many recommend that environmental and ecological assessments be performed based on exergy rather than energy.

For example, exergy has been found to be useful in understanding and assessing:

- environmental impact (Sciubba, 1999; Tribus and McIrivne, 1971; Rosen and Dincer, 1997a, 1999; Gunnewiek and Rosen, 1998; Rosen, 2002a),
- ecology and the wellness of ecological systems (Szargut et al., 2002; Szargut, 2005; Jorgensen, 2000; Jorgensen and Fath, 2004),
- non-renewable resource depletion (Szargut et al., 2002), and
- sustainable development (Dincer and Rosen, 2007).

Several exergy-based environmental and ecological analysis techniques have been developed. Their goals usually include determining appropriate allocations of resources for environmentally responsible or improved design and operation, and/or environmental and ecological impacts. Existing exergy-based environmental and ecological techniques include environomics, exergy-based industrial ecology and exergetic life cycle assessment. These approaches identify as important the exergy of a system as well as associated exergy inputs and outputs. Such knowledge can improve understanding and aid design efforts.

Maintaining ecological integrity is important but complex (Kay and Regier, 2000). Nonetheless, an understanding of ecological integrity is important in regional and global efforts aimed at restoring the environment and protecting human health.

Note that some researchers question whether exergy is adequately related to environmental impact and ecology to form a useful tool. Also, many exergy-based methods are in their infancy and still undergoing development. For instance, difficulties in ecological model development involve parameter estimation and the selection of the best model structure (which requires knowledge of many ecological system properties), and attempts have been made to overcome these difficulties by researchers such as Jorgensen et al. (1995).

Accounting for nature’s contribution to industrial activity is important in determining its impact and sustainability. Decisions based on assessments that ignore nature significantly deteriorate the ability of ecosystems to provide the goods and services necessary for human activity.

1.5. SCOPE AND FOCUS OF THE BOOK

In this book, the relations between exergy and the environment and ecology are described, and many of the techniques which integrate exergy and these topics are reviewed. Numerous applications and case studies are considered, including electricity generation, cogeneration, hydrogen production, biofuels processing and automotive operations.

The book focuses on the fields of engineering and science as well as environmental and ecological management, and is most relevant to energy activities in these disciplines. Economics is also addressed where relevant.

The book covers industrial applications. But since the field of exergy and environmental and ecological management is far from maturity and still developing, relevant research and development initiatives and advances stemming from that work are also covered.

1.6. OUTLINE OF THE BOOK

This book is divided into four parts. The first provides an introduction to the main disciplines involved in the interdisciplinary field of exergy and environmental and ecological management. The second part is dedicated to concepts and methods. Applications are the focus of the third part, while the fourth part presents case studies. The four-part structure of the book is illustrated in Figure 1.1, highlighting the material covered in each of the parts.

In the first part, an introduction is presented that describes the motivation for the book, as well as general material on energy, society, the environment and sustainability. The general area of the environment and ecology and exergy is introduced, highlighting the connections between these quantities, and the history of this interdisciplinary area is outlined.

In the second part of the book, concepts are presented for exergy and its relations to the environment and ecology. Correlations between exergy-based environmental measures and other indicators of environmental or ecological health are explained. Methods integrating exergy and the environment and ecological systems are described. Extensions of exergy-based methods for environmental and ecological management to economics are also covered.

In the third part of the book, a range of applications are described so as to illustrate and clarify the concepts and methods and highlight the potential benefits of using them. As the objectives of exergy-based environmental and ecological management more sustainable designs and operations, the benefits are potentially of significance. The applications are varied and provide useful insights.

In the final part of the book, many case studies are presented to provide detailed examples of applications of the concepts and methods to realistic activities in industry and other parts of society. The case studies are varied and provide practical information.

1.7. CLOSING REMARKS

In this chapter, the motivation for this book on environmental and ecological management is described, with its enhanced approach based on the integration of the environment and ecology with exergy. The motivation is partly based on the need to understand the environmental and ecological implications of processes and systems in order to attain such objectives as environmental protection and sustainability, and the potential complementary and beneficial knowledge that can be provided by new approaches to environmental and ecological management. This approach offers significant potential to improve society's systems, resource utilization and environmental interactions. The idea of a thermodynamic theory of environmental and ecological impact been examined at times in the past, but has not achieved widespread acceptance or adoption. It is hoped this book can contribute to a better acceptance of this idea, by presenting it in a practical form based on exergy. The material should be of great relevance in fields ranging from environmental protection and sustainability to engineering, science, technology and business.

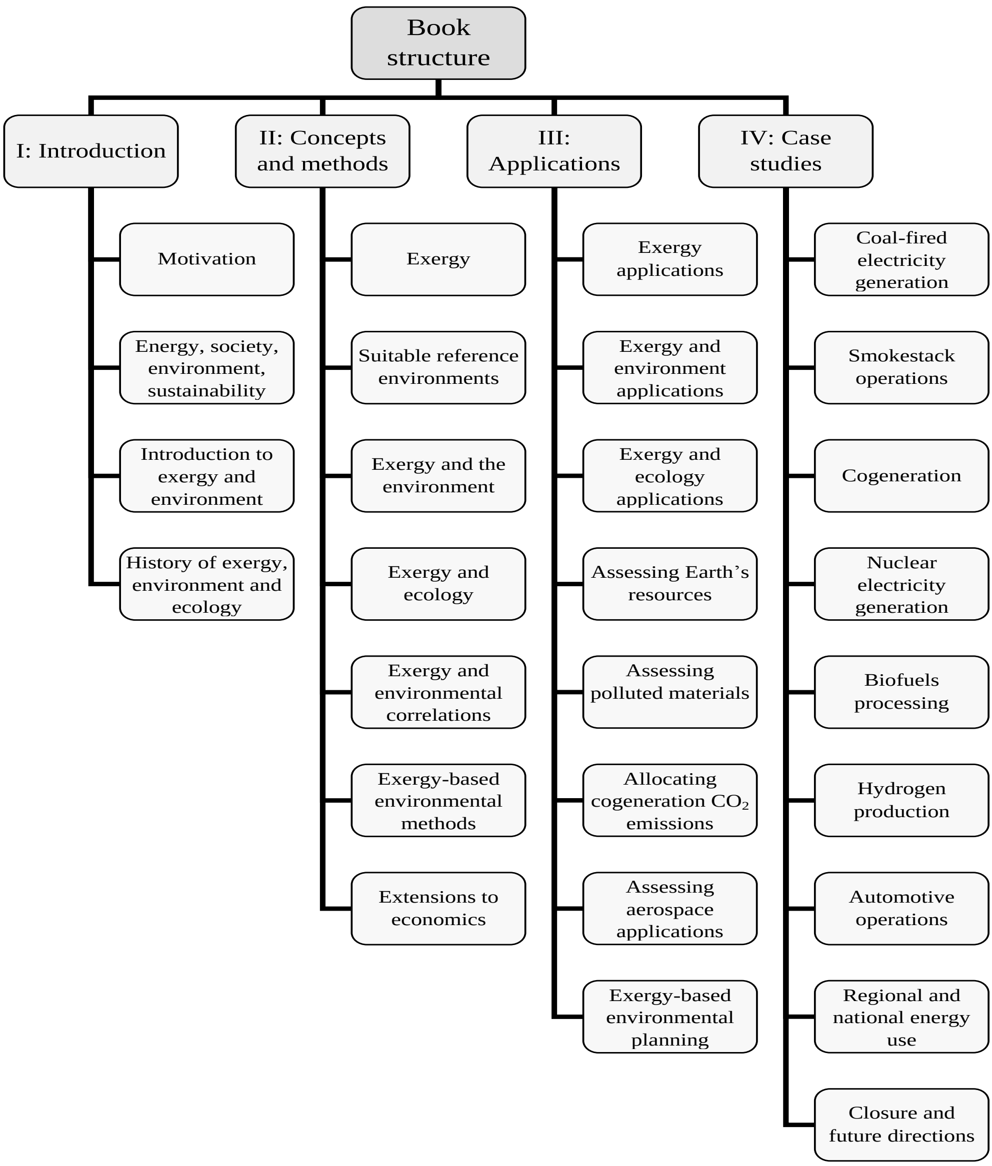

Figure 1.1. Structure of the book, showing details of its four parts.

Chapter 2

BACKGROUND: SOCIETY, SUSTAINABILITY, ENVIRONMENT AND ENERGY

OVERVIEW

Environmental and ecological management relate in many ways to such areas as energy, society, living standards, culture and sustainability. A background understanding of these areas, as well as their interrelations, is useful for readers of a book on a novel approach to environmental and ecological management. Here, living standards, culture and other societal factors are described. Then environmental impact, energy use and design for environment are discussed. Finally, the interrelations are examined between environment and ecology with living standards, culture and sustainability. The differences between developing and developed countries are addressed throughout.

Environment and ecology, and their management, span a wide range of areas, including energy, society, living standards, culture and sustainability. Furthermore, these areas are often interrelated, e.g., availability and use of energy resources often correlate with living standards and culture, while societies with high living standards often have good education systems and undertake research to develop of technologies capable of reducing losses and environmental and ecological impacts.

A background understanding of these areas and their interrelations is useful for readers of this book, and provided in this chapter. We examine important societal factors, as well as sustainability, environmental and ecological factors, energy, and design for environment.

2.1. SOCIETY

In examining societal aspects of environmental and ecological management, it is helpful to briefly review first some key societal factors and indicators.

Table 2.1. Global population (in millions), broken down by region and time*

Region	Year		
	1990	2010	2030
China	1120	1300	1450
India	870	1200	1450
Organisation for Economic Co-operation and Development (OECD) countries	1080	1220	1300
Remainder of developing Asia	760	1100	1300
Africa	620	1000	1450
Middle East	180	200	320
Latin America	360	450	600
Transition economies	320	400	370

* Adapted from data at International Energy Agency (www.iea.org).

Table 2.2. Variation with time of gross domestic product (GDP) (in billion US dollars) using exchange rates, broken down by region

Category	Year				
	1970	1980	1990	2000	2010
Organisation for Economic Co-operation and Development (OECD) countries	10,500	14,900	20,200	28,200	30,000
Africa	280	380	500	600	900
Middle East	220	430	380	520	790
Asia	460	770	1490	2940	8700
Latin America	580	970	1100	1400	2000
World	12,300	17,900	24,300	32,100	40,000

Data source: International Energy Agency (www.iea.org).

2.1.1. Population

The global population is expected to grow from 7.0 billion in 2011 to about 10.5 billion in 2050, while the portion of the population living in developing countries is about 80% and expected to reach about 85% by 2050 (OECD, 1999; WEC, 1995). A breakdown of the global population by region and time is shown in Table 2.1.

2.1.2. Living Standards and Economic Development

Living standard is defined as the "degree of material comfort available to person or class or community," and as "a level of subsistence, as of a nation, social class, or person, with reference to the adequacy of necessities and comforts in daily life."

The gross domestic product (GDP) is shown for many regions in Table 2.2, for the last four decades. Significant disparities exist in wealth and living standards between developed and developing countries.

Table 2.3. Social, economic and development indicators for selected Latin and Caribbean countries (1998)

Indicator	Argentina	Brazil	Colombia	Haiti	Honduras	Mexico	Nicaragua
Population							
Total (million)	36	166	41	8	6	96	5
Urban (% of total)	89	80	73	34	51	74	55
Health							
Life expectancy at birth (years)	73	67	70	54	69	72	68
Infant mortality (per 1000 live births)	19	33	23	71	36	30	36
Child malnutrition (% of children under age 5)	2	6	8	28	25	–	12
Access to safe water							
Urban (% of population)	71	85	88	37	81	91	81
Rural (% of population)	24	31	48	23	53	62	27
Economic/development							
GDP/capita (US$/person)	8030	4630	2470	410	740	3840	370
GDP (US$)	290	768	101	3	5	368	2
Industry portion of GDP (%)	29	29	25	20	31	27	22
Services portion of GDP (%)	66	63	61	50	49	68	44
Poverty (% of population below poverty line)	18	–	18	–	53	–	50
Illiteracy (% of population over age 14)	3	16	9	52	27	9	32

Adapted from The World Bank (2000).
Gross domestic product (GDP) is determined based on Atlas method.

For example, statistics of modern living standards show that per-capita incomes of the population of some lesser-developed countries are less than one per cent of the per-capita incomes of the most developed countries. Adequate supplies of resources like energy are needed to improve living standards in less-developed nations.

Economic development is often viewed as a key factor in attaining high living standards. Numerous social and economic indicators are used to measure living standards (Colonbo, 1992; Hjorth et al., 2000; Haberl, 2006; Niele, 2005). To illustrate, several social, economic and development indicators are listed in Table 2.3 for selected Latin and Caribbean countries.

2.1.3. Technology and Industry

Technology and industry is often regarded as a main contributor to societal well-being, and possession of technology is a source of societal prestige and identity (Dincer and Rosen, 2001b). Technology often helps to integrate societies through shared resource-consumption patterns, values, awareness and communications, but can also stratify socially between wealthy and poor members of a society. The social consequences of deploying technology often depend on the social and institutional context. In some cases, technologies yield benefits that can be supported by social policies.

2.1.4. Culture

Culture is defined as the "particular form, stage, or type of intellectual development or civilization," and as "the concepts, habits, skills, art, instruments, institutions, etc. of a given people in a given period" or "civilization." Factors that contribute to culture include standards for greetings and dress, social taboos, customs, traditions, crafts, local foods, and architecture.

A local culture can be viewed as part of its environment. To be sustainable and responsible, development must be sensitive to its impact not just on the natural environment, but also on the local culture. Some argue that cultural diversity is as important to the planet's survival as biodiversity, but is probably more endangered and less protected. Preserving cultures can be challenging because, even though part of a culture is easily observed, its essence is often hidden and not shared with outsiders. Also, determining the "positive" elements of a culture and its development is subjective and based on one's values and experiences.

2.2. Sustainability and Sustainable Development

The 1987 Brundtland Report of the World Commission on Environment and Development defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." This definition implies that actions of present societies should not threaten existing cultures and their evolution, or future living standards.

The degree to which sustainable development can be achieved by countries varies, since countries differ according to such characteristics as size, wealth, living standards, culture, and political and administrative systems. Wealth and advanced technology may make it easier for industrialized countries to strive for sustainable development. However, the reversal in the trend towards declining carbon emissions that occurred after the oil-price decline in 1986 illustrates that this concept does not always apply. The basic motivations and desires of societies, countries, cultures and people appear to have not changed, and these aspirations often require increasing energy use and often yield correspondingly increased emissions.

Transforming behavioral and decision-making patterns requires recognition that current development paths are not sustainable. History suggests that such recognition occurs only when short-term consequences are obvious, as in the case of an "oil-price shock" or a disaster such as a drought. To successfully mobilize the resources needed to reduce the risks associated with environmental issues, society must perceive the potential long-term consequences associated with present behavior patterns. Translating the future threats associated with continual increases in energy use and carbon emissions into immediate priorities is and will likely remain one of the most difficult challenges facing policy makers.

Effort is now being devoted to applying sustainability concepts in various areas. For instance, sustainable engineering has been the focus of recent books (Graedel and Allenby, 2010; Brennan, 2012), which cover concepts and strategies, applications and implementation, and criteria and evaluation. Also, the development of a sustainability science based on thermodynamics has also been investigated (Gutowski et al., 2011), as has the use of metrics from thermodynamics in sustainable technology development (Van der Vorst et al., 2011).

2.3. Environmental and Ecological Concerns

Many types of environmental concerns exist, varying from local and regional to multi-national and global, with some of the most significant problems like global climate change and ozone depletion falling into the latter category. Environmental and ecological impacts differ markedly by country. The U.S., for instance, is presently responsible for approximately 23% of total global greenhouse gas emissions. On a per capita basis, industrialized countries are responsible for most air pollution, ozone depletion and carbon emissions. Per capita contributions from developing countries are smaller, but are increasing rapidly as they industrialize. Most countries began addressing environmental problems seriously in the 1980s, adopting policies and strategies to foster economic development and environmental stewardship. Addressing environmental issues has become part of the culture of some countries.

Ecosystems are fragile and resources are scarce in many regions, and ecosystem protection requires that activities be carefully managed. Air, land and water are being degraded in most areas, and life forms such as mammals, birds, reptiles, plants and aquatic life are threatened. Many of these concerns are associated with the use of resources (e.g., material feedstocks, energy), but in many countries supply options are limited. Resources are either imported, using foreign exchange which might otherwise be used for purchasing items such as educational materials, medicine or other development needs. Alternatively, resources are obtained locally, e.g., energy from local biomass. Large-scale consumption of biomass resources, however, leads to air and water pollution, deforestation, soil erosion and global climate change.

Environmental and ecological policy alternatives are complex. Problems such as acid precipitation can be dealt with in part by technical and regulatory measures, e.g., societies can implement vehicle exhaust standards or emission limits for power stations. Such measures impact a relatively focused and small number of parties. But greenhouse gas emissions, which are attributable to many sources and affect large geographic areas, require comprehensive energy policies that cross many countries, as local and relatively narrow approaches are generally of limited effectiveness.

Environmental and ecological protection programs are expanding in many countries, e.g.,

- many efficiency improvement and conservation measures have been applied,
- regulations and standards for have been developed or strengthened,
- incentives have been put in place to stimulate investments in environmental equipment,
- auditing and reporting procedures have been launched, especially for industries, and
- relevant research and development have been promoted.

But environmental and ecological protection programs are not undertaken on a significant scale in many countries for various reasons (Painuly and Reddy, 1996), including technical difficulties (e.g., lack of reliable and efficient technologies), managerial and institutional barriers (e.g., lack of appropriate technical input, program-design and monitoring expertise; inadequate program-management and training), economic shortcomings (e.g., lack of financing mechanisms; inappropriate pricing of commodities), and inadequate information transfer (e.g., lack of information on technologies and related matters).

Achieving the potential gains associated with environmental and ecological management requires efforts by consumers, manufacturers, suppliers and governments. Mechanisms are needed to encourage cooperation and to overcome the potential obstacles to efficiency improvement. For example, incentives can be provided such as tax breaks to improve the efficiency of providing products and services. Incentives for the accelerated replacement and decommissioning of inefficient equipment can also be beneficial. Of course, practical limitations exist on increased efficiency, due to factors like economics, sustainability, environmental impact, safety, and societal and political acceptability, and the desired balance among these factors often affects living standards and depends on a society's culture.

Addressing environmental and ecological concerns, while accounting for existing and desired living standards and culture, requires long-term strategic planning. Otherwise, actions are likely to be inefficient, ineffective and uncoordinated and their potential benefits not fully achieved. For example, "New Earth 21" was proposed in the 1990s as a long-term and comprehensive strategic plan that all countries can undertake cooperatively to address environmental degradation and achieve sustainable development (Okamatsu, 1992). The plan includes worldwide promotion of efficiency and conservation (within 10 years), large-scale introduction of clean energy resources, including renewable and nuclear energy (within 20 years), and development of innovative technologies (50 years). Promotion includes increasing public awareness of the benefits through education and training, and encouraging the development of comprehensive policies, particularly in areas of public welfare, transportation and industry. The degree to which strategic plans prove acceptable or implementable in a country depends largely on its culture and living standards, although their adoption can affect future living standards and cultural development.

Depending on the culture and values of a society, environmental and ecological measures can sometimes be introduced voluntarily and have substantial success. In other situations, governments must use incentives and enforcement measures such as laws and penalties to achieve significant benefits. For example, the combination in North America of inexpensive energy supplies and moderate environmental constraints have led to a culture of travel by automobile and less preference for public transit, making it difficult in that society to substitute public transit for automobile use. The success of such initiatives can nonetheless be noteworthy, e.g., if one percent of the cars in the U.S. were tuned, gasoline consumption would decline and about one billion pounds of CO_2 emissions would be avoided.

2.3.1. Climate Change

Many studies suggest that increasing emissions of greenhouse gases (CO_2, CH_4, CFCs, halons, N_2O, ozone, peroxyacetylnitrate) are increasing atmospheric concentrations of these greenhouse gases (GHGs) and leading to changes in the global climate over the next century.

Most investigators agree that increasing GHG concentrations are increasing the amount of heat radiated from the Earth's surface that is retained, thereby disrupting the Earth-sun-space energy balance (see Figure 2.1) and raising the mean surface temperature of the Earth (i.e., causing global warming). For instance, many believe that the mean surface temperature of the Earth has increased by about 0.5-1.5°C over the last century, and that the sea level has consequently risen by 10-30 cm. Data on these parameters are listed in Table 2.4. Future predictions range widely, but most suggest that the temperature rise by 2100 may be restrained to 2-4°C with aggressive measures, and may reach 5-8°C without such measures.

Data for various greenhouse gases are shown in Table 2.5. The atmospheric concentrations for these gases are seen in columns 2 and 3 to have increased since pre-industrial times. The main contribution to the greenhouse effect can be observed in column 4 to be associated with carbon dioxide. Nonetheless, the contribution to the greenhouse effect is seen in the last column to be greater, on a per molecule basis, for other greenhouse gases.

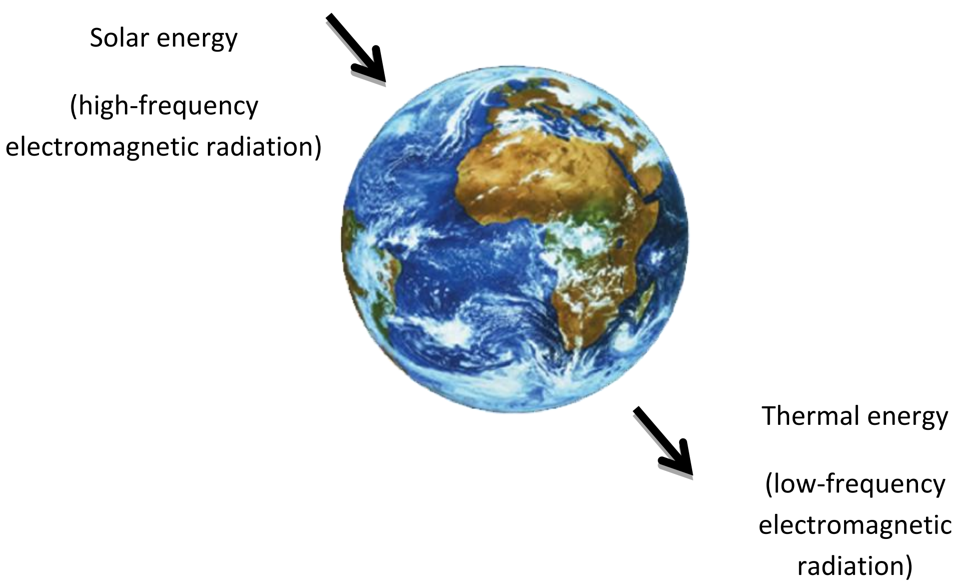

Figure 2.1. Earth-sun-space energy balance, showing main external flows: solar energy input and heat emission to space at a lower frequency.

Table 2.4. Selected environmental data

Parameter	Year							
	1860	1880	1900	1920	1940	1960	1980	2000
Mean temperature at Earth's surface (°C)	14.5	14.6	14.8	14.7	15.0	15.0	15.1	15.3
Atmospheric CO_2 concentration (ppm)	283	290	292	298	308	311	330	370

Adapted from (Colonbo, 1992).

Table 2.5. Contribution to the greenhouse effect of selected greenhouse gases

Substance	Atmospheric concentration (ppm)		Anthropogenic share in greenhouse effect (%)	Ability to retain infrared radiation (relative to CO_2)
	Pre-industrial	1990		
CO_2	275	346	71	1
CH_4	0.75	1.65	8	25
N_2O	0.25	0.35	18	250
R-11	0	0.00023	1	17,500
R-12	0	0.00040	2	20,000

Adapted from Aebischer et al. (1989).

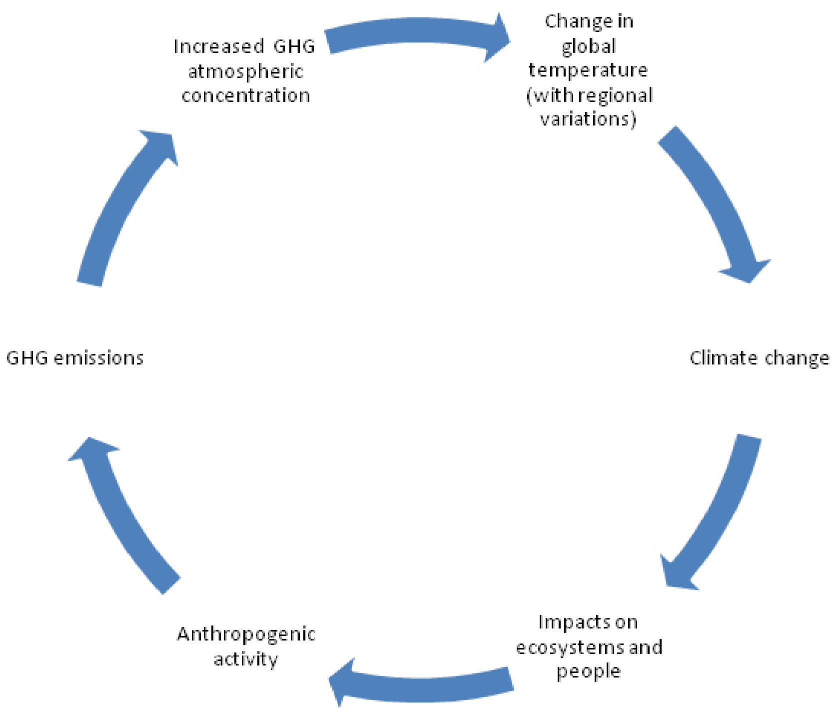

Figure 2.1. Cycle of actions that lead to climate change and may motivate actions to mitigate it. The cycle starts with anthropogenic activity, which leads to GHG emissions. The eventual impacts on ecosystems and people may motivate anthropogenic activities to mitigate and/or adapt to climate change.

Activities that lead to climate change (sometimes referred to as global warming) are shown in Figure 2.1, where it is seen that emissions of greenhouse gases from anthropogenic activity are a prime driver. Humanity is contributing through many of its economic and other activities. Carbon dioxide, the most significant greenhouse gas, mainly results from the combustion of fossil fuels, which account for the great majority of energy use globally. This point is illustrated Table 2.6, which shows past and predicted future CO_2 emissions from fuel use. Other sources of GHG emissions include methane emissions from human activity (e.g., natural gas leaks, coal mining), CFC releases and deforestation. Energy-related activities are clearly major emitters, direct and indirect, of greenhouse gases.

Table 2.6. Variation with time of fuel-related annual global emissions of carbon dioxide (in Gt) broken down into several categories

Category	Year					
	1980	1990	2000	2010	2020	2030
Fuel source						
Coal/peat	5.7	7.2	6.5	10.7		
Oil	7.8	8.1	10.0	11.1		
Natural gas	3.5	4.2	5.0	5.4		
Socioeconomic grouping						
Organisation for Economic Co-operation and Development (OECD) countries	10.9	11.0	11.8	12.6	13.5	14.4
Developing countries	3.5	5.0	7.3	12.0	15.6	20.9
Transitioning economies	3.6	3.5	2.4	2.6	2.7	2.8

Data source: International Energy Agency (www.iea.org).

Characteristics of carbon dioxide sources help illustrate the causes of climate change, and some of these are illustrated from fuel-related sources over time in Table 2.6. Specifically,

- fuel-related global carbon dioxide emissions are broken down by fuel source in one part of the table, and
- these emissions are broken down by socioeconomic category (developing, transitioning and OECD countries) in another part of the table (for predicted future as well as past years).

Climate change has been demonstrated by many to have a wide range of potential effects on human activities around the world and to be a significant risk to humanity. For instance, many predict that, if past fossil fuel use trends continue and atmospheric concentrations of greenhouse gases continue to increase, the Earth's mean surface temperature will increase by 2-6°C and the sea level will rise by 30-60 cm by 2100, and various disruptions will ensue:

- flooding of coastal settlements,
- displacement of fertile zones for agriculture and food production toward higher latitudes, and
- decreasing availability of fresh water.

Climate change has thus become a significant concern to policy makers and the public. These concerns are also shown in Figure 2.1, in that the eventual impacts of GHGs on ecosystems and people may motivate activities to mitigate and/or adapt to climate change.

Options that have been investigated for stabilizing climate change by restraining emissions of greenhouse gases include efficiency improvement, energy conservation, and fuel substitution. Given the limited alternative resources of oil and gas in most jurisdictions, the potential for switching among domestic fuels is limited and, because of poor financial resources in many countries, especially developing ones, the prospect of importing cleaner fuels is of limited potential. Achieving the possible benefits of improved energy efficiency will require a concerted effort on the part of consumers, manufacturers, energy-supply companies and governments.

Both industrialized and developing countries must be involved in strategies to mitigate climate change. Predictions vary, but many suggest that about 60-70% of the rise by 2100 in the mean global surface temperature associated with climate change may be attributable to emissions from developing countries (Lashof and Tirpak, 1991; Sathaye and Ketoff, 1991). Many estimate, based on various scenarios, that developing countries are the most rapidly increasing source of CO_2 emissions and will be the largest source of total emissions. China in particular has been identified as a major contributor to total GHG emissions. Measures to mitigate global climate change have costs, which significantly affect the type and level of implementation. In developing countries, these costs are weighed against numerous other needs (e.g., investments in health care, education, economic development), and thus a balanced approach is required.

It is noted that some people dispute aspects of the climate change, including the type and level of actions that are required to mitigate it.

2.3.2. Stratospheric Ozone Depletion

Ozone in the stratosphere, at altitudes of 12-25 km, absorbs ultraviolet (UV) radiation and thus helps maintain an equilibrium for the Earth. Stratospheric ozone depletion can lead to increased levels of damaging UV radiation reaching the ground, causing increased rates of skin cancer, eye damage and other harm to many biological species. The regional depletion and distortion of the stratospheric ozone layer has become a global environmental concern.

Stratospheric ozone depletion has been shown to be attributable to chlorofluorocarbon (CFC), halon (chlorinated and brominated organic compounds) and N_2O emissions. There exist both natural and anthropogenic causes of stratospheric ozone depletion. Energy-related activities create some of the emissions, directly or indirectly, which lead to stratospheric ozone depletion. For instance, CFCs, which are used in air conditioning and refrigerating equipment as refrigerants and in foam insulation as blowing agents, play the most important role in ozone depletion, while fossil fuel and biomass combustion account for approximately 70% of anthropogenic N_2O emissions. Replacement equipment and technologies that do not use CFCs are gradually coming to the fore and may ultimately allow for a total ban of CFCs. An important consideration in such a CFC ban is the need to distribute fairly the economic burdens deriving from the ban, particularly with respect to developing countries, some of which have invested heavily in CFC-related technologies.

An international protocol was signed in Montreal in 1987 to reduce the production of CFCs and halons, and commitments for more drastic reductions in their production were undertaken at the 1990 London Conference.

2.3.3. Acid Precipitation

Acidic substances are produced by the combustion of fossil fuels, in such devices as transportation vehicles, industrial boilers and smelters. Acid precipitation refers to the situation in which these substances are transported through the atmosphere, sometimes over large distances, and deposited via precipitation on the Earth. The main sources contributing to acid precipitation are coal and high-sulfur fuel oil.

Some ecosystems are vulnerable to damage from excessive acidity. The effects of acid precipitation include

- acidification of lakes, streams and groundwaters, resulting in damage to fish and aquatic life,
- damage to forests and agricultural crops, and
- deterioration of materials, e.g., buildings, metal structures and fabrics.

Acid precipitation is mainly attributable to emissions of SO_2 and nitrogen oxides (NO_x), although contributions are also made by such other substances as volatile organic compounds (VOCs), chlorides, ozone and trace metals that may participate in the complex set of chemical transformations in the atmosphere resulting in the formation of acid precipitation (in addition to other air pollutants). Some energy-related activities are major sources of acid precipitation:

- NO_x emissions are strongly related to road transport, which accounts for about half of the total in OECD countries. The contributions of vehicle exhausts are anticipated to increase, as the global number of cars and light trucks has been continually climbing, reaching approximately 800 million in early 2007.
- About 80% of SO_2 emissions stem from electric power generation, residential heating and industrial energy utilization, especially where coal is used.
- H_2S, which can react to form SO_2 when exposed to air, stems from sour gas treatment.
- VOCs are generated by many sources, and include various diverse compounds.

The most significant contributors to acid precipitation include the United States, China and Europe. A particular difficulty with acid precipitation is that its effects are diffuse and often cross borders as acidic substances are transported through the atmosphere. Measures for controlling acid precipitation include enhancing the efficiency and environmental controls for vehicles and other technologies, offsetting vehicle use through mass transit, substituting clean energy forms for fossil fuels, and using fossil fuels more cleanly.

2.3.4. Water and Soil Degradation

Clean groundwater and surface water is important in many parts of the world, particularly as a source of drinking water.

Groundwater degradation concerns are of two main types: 1) quantity, because groundwater extraction reduces groundwater supplies, and 2) quality, as groundwater purity can be degraded through pollution. Groundwater can be contaminated by sewage disposal, agricultural activity, solid waste disposal in landfills, liquid waste disposal in wells, releases or leakages of petroleum and other chemicals substances, road salt runoff, and pesticide and herbicide application. Soil often filters, buffers and dilutes contaminants as they seep through to the groundwater, but this effect varies with soil type.

The quality and chemical composition of surface waters is affected by the natural environment itself (e.g., configuration, nature of surrounding lands), as well as human activity. Human-related changes in surface-water chemical composition are usually caused by direct emissions (e.g., fertilizer or industrial waste discharges), and/or indirect emissions (e.g., deposition of atmospheric contaminants on waters, acid precipitation). Some of the main concerns regarding surface water quality are acidification of lakes and rivers (noting that the level of acidification varies for each body of water, as some can buffer the effects better than others depending on the characteristics of the adjacent soil and rock), eutrophication (i.e., a lack of accessible oxygen due to excess biological activity, often from an oversupply of nitrogen and phosphorus from fertilizer runoff), siltation, normally due to construction and forestry activity, and pollution from discharges of toxic organics, heavy metals and salts.

Human activities and soil erosion are rendering much arable land unusable for agricultural purposes, by degrading soil quality. Increased future needs for food, particularly as global population increases, may increase the magnitude of the impact of this problem.

2.3.5. Air Pollution, Smog and Indoor Air Quality

Air pollution can lead to a variety of impacts on the ambient atmosphere. Air pollution is caused by emissions of toxic gases such as SO_x, NO_x, CO, VOCs, and particulate matter (e.g., fly ash and suspended particles). Excessive concentrations of these pollutants and of ozone have been demonstrated to cause health and ecological effects felt locally and sometimes regionally. Air pollutants are emitted from various stationary and mobile fuel consumption sources, and energy-related activities contribute significant quantities of all of these pollutants. Regulations on emissions are often used to reduce air pollution, and high chimney stacks are used to alleviate localized air pollution (i.e., transport pollutants elsewhere).

Smog can cause health and crop damage. Ozone (O_3) is the main constituent of photochemical smog, which is produced near the ground and at low levels in the atmosphere. Ground-based ozone formation can be controlled by limiting atmospheric emissions of non-methane hydrocarbons (NMHCs) such as ethylene, butane, etc., and/or nitrogen oxides (NO_x) (mainly NO and NO_2), particularly from such activities as electricity generation using fossil fuel combustion, and the use of automobiles and other fossil fuel-fired transportation devices.

Hazardous air pollutants are of particular concern, and are usually emitted in smaller quantities than those that are the focus of general air quality concerns. Lead is the main hazardous air pollutant, and most of the world's lead pollution comes from the use of lead-based gasoline additives to increase octane ratings. Lead exposure may cause neurological damage. Since the 1970s many countries have taken steps to phase out these lead-based additives (Haberl, 2006). Additionally, the number of suspected hazardous pollutants is very large and knowledge of sources, emissions and effects is still developing. The concern is both localized where micro-pollutants are discharged, and regional for toxic pollutants, e.g., cadmium, mercury and polycyclic aromatic hydrocarbons. Many energy-related activities emit hazardous air pollutants, e.g., hydrocarbons such as benzene, emitted fugitively from oil and gas extraction and processing industries; hydrocarbon and dioxin emissions caused by the use and combustion of petrol and diesel oil for transport; small quantities of arsenic, mercury, beryllium and radionuclides released during the combustion of coal and heavy fuel oil; and mercury, chlorinated dioxin and furan emissions from municipal waste incinerators.

Indoor air pollution is also of concern (e.g., CO, CO_2, and smoke from stoves and fireplaces; various gaseous oxides of nitrogen and sulfur from furnaces; stray natural gas and heating oil vapors; radon emitted by natural gas burning appliances and the surrounding soil; cigarette smoke, and formaldehyde from plywood and glues). Ventilation even in tightly sealed energy-efficient buildings can eliminate most indoor air quality concerns.

2.3.6. Habitat and Biodiversity Reduction

Many flora and fauna species are becoming extinct, often due to human activity, leading to a range of impacts such as disruptions of food cycles and reductions of the genetic pool (which may, for example, limit potential for new drugs and new forms of biomass energy), as well as ethical concerns. These reductions in biodiversity are in large part caused by losses of and/or disruptions to natural habitats due to urban expansion, expanded agricultural uses, and deforestation for a range of purposes. In particular, the large continuous tracts of land that are needed for some species are being disrupted.

2.3.7. Hazardous Waste Disposal and Herbicide and Pesticide Use

Hazardous wastes contain toxic materials, e.g., benzene, PCBs, lead, arsenic, cadmium, pesticides and herbicides. If these escape during disposal or from their disposal locations (e.g., hazardous waste sites), they can cause ecological harm to nearby systems and degrade groundwater quality.

The use of herbicides and pesticides is inherently of concern environmentally as such use is intended to harm selected biological systems. The unwanted environmental and biological damage caused by herbicides and pesticides is affected by the toxicity of the compounds used, the longevity of the compounds in the environment and the application intensity and methods. Pressures for increased food production tend to lead to increased use of herbicides and pesticides, but studies indicate that their uses can be reduced through careful optimization for minimal undesired environmental impact, and/or use of alternate control methods for harmful pests and plants.

2.4. Energy

2.4.1. Energy Use Patterns

Between 2000 by 2050, it is anticipated that world energy use will increase by almost an order of magnitude and primary energy demand by up to three times, with economic development and population growth being the main drivers. Several methods are used by to project future energy use, by organizations such as the International Energy Agency. Annual global use of primary energy is shown in Table 2.7, along with its variation over time.

Table 2.7. Variation with time of annual global use of primary energy (in Gtoe)

Primary energy form	Year			
	1980	1990	2000	2010
Coal/peat	1.6	2.0	2.0	2.6
Oil	3.0	3.1	3.5	3.9
Natural gas	1.4	1.8	2.0	3.3
Nuclear	0.1	0.2	0.5	1.3
Hydro	0.03	0.04	0.06	0.06
Combustible renewable energy and waste	0.7	1.0	1.1	1.2
Other primary energy (solar, wind, geothermal etc.)	–	–	–	–

Data source: International Energy Agency (www.iea.org).

Energy-use patterns in countries differ markedly. Globally, for instance, 20% of the population accounts for 70% of energy use. The U.S., for example, is responsible for approximately 25% of total world energy consumption. An average U.S. person consumes 230,000 kilocalories daily of food energy, 115 times the 2000 kilocalories needed to survive. A typical Western European uses as much energy as 80 people in sub-Saharan Africa. If the rest of the world were to use energy at the same rate as the U.S., world energy use would increase by about four times, and environmental impact would increase many times more.

Developing countries are responsible for only a quarter of global energy use, but their use of energy is growing rapidly as demand increases due to rapid population growth, economic development and urbanization. The energy needs of cities are significant and increase with both urban growth and industrial development, as urbanization shifts societal energy use from traditional fuels (e.g., wood) to electricity and fossil fuels.

Energy processes and utilization lead to numerous environmental and ecological concerns (climate change, stratospheric ozone depletion, acid precipitation, smog, etc.), leading many countries and regions to undertake extensive environmental assessments prior to approving and implementing new energy systems or major modifications to existing ones. These concerns are increasing rapidly for developing countries and countries with emerging industrial economies, as their energy-consumption growth rates are high while their environmental management practices are often not stringent.

2.4.2. Options to Address Energy Issues

Solutions to energy problems that can improve living standards can be technical and non-technical (e.g., reducing energy usage by changing life styles and increasing public awareness and education). There are many ways to reduce energy use:

- *Increased efficiency*. Efficiency measures can often be implemented quickly for devices with rapid turnover, e.g., light bulbs, refrigerators, cars, while power stations and similar infrastructure typically have much longer lifetimes. Efficiency improvements can also enhance the reliability of energy supplies and improve their longevity (Graedel and Allenby, 2010; Painuly and Reddy, 1996). Despite high initial capital costs, efficiency measures can result over time in considerable economic savings for both individuals and societies. An example of the latter case is the elimination of the need for new power stations through high-efficiency electricity utilization. Additionally, efficiency measures can slow growth in energy use and carbon emissions, although it likely cannot offset the increasing energy use in many developing countries to support economic growth. Significant decreases in the energy requirements for economic development probably require more fundamental changes in such societies and the way they develop. Industrialized countries, for example, usually exhibit continually increasing energy use and carbon emissions due to the desire for greater comfort and convenience. Many developing countries have followed the development of industrial ones, often leading to urban blight and other problems. Efficient energy use is particularly important to developing countries, as it can forestall the need for large capital investments. Developing countries often lack financial resources, and investment in efficient new technology is typically much less expensive than retrofitting old plants. Expanding the economies of developing countries using modern technology allows them to bypass the inefficient technologies used in industrialized countries in the past.

- *Greater use of renewable energy resources*. This measure decentralizes the energy supply and allows for greater participation in energy decisions. For example, solar-related energy technologies offer greater local participation in energy decisions, and have the flexibility to adapt to local conditions, costs and benefits. The U.S. could reduce its annual energy consumption by 50% by 2030 with efficiency increases and use of renewable energy (Rosen, 2002d).
- *Improved supportive measures*. These include the use of appropriate energy regulations and standards, especially for automobiles and buildings; appropriate energy pricing policies and financial incentives; enhanced maintenance and operation practices as well as energy auditing, efficient and effective load-management strategies, and targeted energy research. For example, tax incentives can be provided to improve the efficiency, and accelerated replacement and decommissioning of inefficient equipment can also be beneficial. Significant reductions in consumer energy costs occur in many instances when appropriate energy-conservation measures and programs are implemented, and the payback period is often less than two years.
- *Cooperation*. Achieving the potential gains associated with energy measures and strategies requires cooperative efforts by consumers, manufacturers, energy suppliers, governments and sometimes others.

2.4.3. Hydrogen Economy

The world has a numerous energy sources which can be used directly or converted to energy carriers (electricity, heat, chemical fuels). Energy sources like fossil fuels are also energy carriers in that their energy can be transported to and used by energy consumers in the same form as it is found, while other energy sources (falling water, solar radiation, etc.) must first be converted to an energy currency (commonly, electricity) before the energy can be used. Although fossil fuels are presently the main energy sources and energy carriers in the world, sustainable energy sources will be increasingly sought as fossil fuel supplies become scarcer and environmental and other energy-related concerns increase.

Foreseeable future energy sources (falling water, solar radiation, uranium, wind, tides, waves, fusion fuel, etc.) cannot act as energy carriers, and these sources are mainly used at present to produce the energy carrier electricity. Yet people and societies cannot operate effectively with energy provided only in the form of electricity, as they also need chemical fuels and feedstocks (e.g., transportation vehicles, especially airplanes, are difficult to operate economically using electricity, suggesting the need for some chemical fuel, either directly from non-hydrocarbon energy sources or from the electricity they can produce). Many believe that hydrogen is the most logical choice as a chemical fuel in future societies, and that societal energy systems will eventually converted into a "hydrogen economy," where hydrogen and electricity serve as complementary secondary energy carriers (Marban and Valdes-Solis, 2007; Sigfusson, 2007; Lattin and Utgikar, 2007; Scott, 2007; Balat, 2008; Muradov and Veziroglu, 2008; Bose and Malbrunot, 2007; Penner, 2006; Shoko et al., 2006).

2.5. Design for Environment

Design is the act of creating a product or process to satisfy a needed service, and usually involves many steps. Numerous factors are considered in design (e.g., ability to meet need, customer satisfaction, safety, economics, manufacturability, materials and equipment requirements, efficiency, reliability, lifetime, legal/regulatory compliance). A relatively recent addition to the list is "environmental impact," which includes the effects of resource use, emissions and other forms of pollution on ecosystems and other facets of the natural environment. The inclusion of environmental considerations in design is often referred to as Design for Environment (DFE) (Fiksel, 1996; Graedel and Allenby, 2010), and such ideas are often linked with manufacturing (Gungor and Gupta, 1999) and supply chains (Ji, 2009).

DFE considers environmental concerns throughout a design process and is best addressed early, as it is usually easier to alter designs for better environmental and ecological performance in the initial work phases rather than as an afterthought. DFE methods vary in rigor and comprehensiveness, and are often more effective and efficient when implemented in the initial steps of a process. For example, it is often simpler and less expensive to reduce acid gas emissions by removing sulfur compounds from process feedstocks, than by adding capture and treatment steps to the end of a process. The long lifetimes of many products and processes, often ranging from years to decades, make DFE decisions very important, as the impacts of such decisions persist for corresponding durations. Options such as repairing, reconditioning, remanufacturing and recycling to reduce wastes have been examined and contrasted (King et al., 2006).

Energy efficiency and selection are important DFE factors. Design for environment activities related to energy often are aimed at using energy efficiently, and/or using benign energy sources that do not impact negatively on the environment and that are sustainable, i.e., appropriate energy selection. Appropriate energy selection refers to the selection of appropriate energy forms to meet energy needs. For example, energy from wind (commonly electricity) might be good choice for powering lights, while energy derived from natural gas might be more useful for process heating. The inverse, heating with wind-derived electricity or powering lights with natural gas, likely are less appropriate choices for several reasons, including the need such choices introduces for additional energy-conversion equipment.

2.6. INTERRELATIONS

Technical, economic and societal factors are often interrelated. For example, a large population can provide the human resources that help in attaining high living standards in some situations, or can become a burden that leads to lower living standards in others. Cultural choices made by a society (e.g., valuing wealth) can also affect living standards. Furthermore a society with high living standards may have free time to devote to cultural development, while one with lower living standards may focus on practical skills and basic necessities. Technology and society are also related, with technology often affecting social, cultural and living standards.

An abundance of resources can help a society achieve high living standards and economic prosperity, simply through harvesting the resources, although environmental degradation can also result. By extension, cultural choices, directions and development each can be affected by availability of resources. Yet the possession of abundant resources does not always lead to high living standards, and countries that have little or no domestic energy resources can often achieve high living standards, often through developing a culture that highly values learning, knowledge and innovation. Energy choices are sometimes dependent on a society's culture, while at other times energy-related factors contribute to cultural changes and development (Haberl, 2006; Niele, 2005).

Environmental impact is often a significant consequence of energy use (Bisio and Boots, 1996; Perman et al., 1996; Rosen and Dincer, 1997a; Speight and Lee, 2000; Rosen, 2002a, 2004; Dincer and Rosen, 1998, 2001a) and strongly affects and is affected by living standards and culture. Environmental issues also affect the sustainability of a country's development in the longer term (Goldemberg et al., 1988; The World Bank, 2000; Brownsword et al., 2005) and thus are an important consideration in discussions of living standards and culture. This is seen in historical data for global energy-resource use (Table 2.7) and environmental data and related environmental emissions (Table 2.6). For example, increasing use of fossil fuels is seen to correlate with increasing an CO_2 concentration in air.

Energy processes and use impact living standards and culture, while these topics in turn often affect energy choices. Natural energy, which includes direct solar radiation, its derivatives such as wind and wave energy as well as geothermal and tidal energy, makes possible the existence of life, ecosystems and human civilizations. Additional energy, which includes the secondary flows of energy produced by humankind, contributes to advanced technological stages of production and influences the evolution of living standards. Civilizations generally adapt to their environments, developing their own systems of values, consumption patterns for energy and other resources, and development paths. Note that increasing the efficiencies of energy systems often can improve living standards and personal fulfillment, and that significant reductions in energy use can in many instances be attained with little sacrifice of quality of life. An examination of 35 industrialized nations showed no correlation between energy use and a wide set of social indicators (including life expectancy, literacy, unemployment, crime, suicide rates, environmental quality indexes) (Rosen, 2002d).

Another study showed that Sweden has a per capita GDP near to that for the U.S., but outranked the U.S. on almost every other social indicator while consuming 40% less energy per capita (Rosen, 2002d). Some factors contributing to this difference include transportation variations (e.g., higher gasoline taxes, smaller cars, better public transportation and geographic compactness in Sweden), and less wasteful commercial and residential energy use. With changes in lifestyle, energy use can be further decreased.

As an example of the relation between societal factors, consider China. Resource use in that country has been growing markedly since about 2000, especially in urban areas, leading to such benefits as improved living standards and increased affluence, which in turn have led to changes in culture, including a trend towards greater consumption of resources and a stronger desire for consumer goods. Challenges also result from these changes, including increased pollution and scarcities of material and energy resources within the country and beyond. The change in cultural behavior can in turn fuel further increases in demands for resources, leading to a spiral effect where increased resource use improves living standards and changes culture, which in turn leads to further increases in resources use.

Policy makers now focus increasingly on environment and sustainability. For example, incentives are often used to reduce environmental and ecological impact by increasing efficiency and/or substituting more environmentally benign resources for damaging ones. Such actions can make development more sustainable and improve living standards through a cleaner environment. Policies often reflect the concept that consumers share some responsibility for pollution and its impact and cost. Price increases to account for environmental costs have been implemented for resources in some locations.

2.7. Closing Remarks

Environmental and ecological management, energy, design for environment, society, living standards, culture and sustainability are interrelated in diverse and complex ways. For instance, energy impacts a society’s environment, living standards and culture. The background in this chapter on these areas, as well as their interrelations, is important for readers of a book on a novel approach to environmental and ecological management.

Chapter 3

AN INTRODUCTION TO THE ENVIRONMENT, ECOLOGY AND EXERGY

OVERVIEW

One way to better understand and address environmental concerns is to focus on the linkages between exergy and the environment and ecology. Although significant advances have been made in this area in recent years, more research is needed if the benefits—which are potentially immense—are to be fully tapped. The reasoning for these views, which are the focus of this book, is introduced in this chapter.

The topic of energy and the environment has become more and more commonly encountered over the last 20 years or so. Certainly, little attention was paid to the environmental impacts of processes before then. Today, environmental issues that are directly or indirectly related to energy are regularly discussed, and include the following:

- Global climate change, particularly global warming, due to emissions of GHGs
- Stratospheric ozone depletion
- Acid precipitation and deposition
- Air pollution, smog and air-quality and visibility degradation
- Water pollution, including groundwater and surface water degradation
- Solid waste disposal
- Hazardous waste disposal
- Soil degradation
- Oil spills and other major environmental accidents
- Radiation and radioactivity releases

However, many proponents of exergy methods have suggested that it is more appropriate to focus not on energy and the environment, but rather on exergy and the environment, a view that motivated the writing of this book. In this chapter, the topic of exergy and its relation to environmental and ecological impact is introduced.

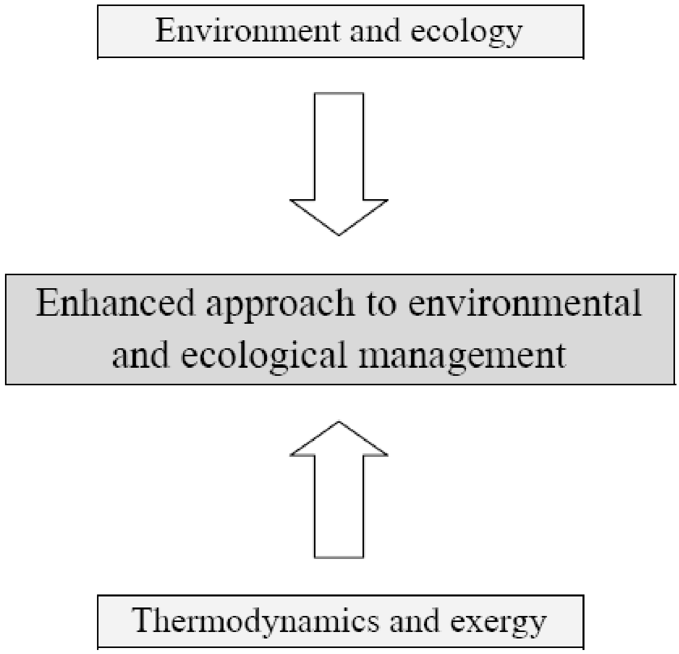

Figure 3.1. Illustration of the integration of environmental and ecological disciplines with thermodynamics and exergy for an enhanced approach to environmental and ecological management.

The fundamental concept of this book is summarized in Figure 3.1, which describes illustratively the intent of this book: to combine environmental and ecological disciplines with thermodynamic methods, especially those using exergy, to obtain an enhanced approach to environmental and ecological management.

3.1. How Does Exergy Relate to Environmental Impact?

There are many justifications, some of which are compelling and thought provoking, for the view that the link between exergy and the environment is more important than that between energy and the environment.

Exergy analysis is, first and foremost, a powerful tool for improving the efficiency of processes and systems. And, simply put, any measures that increase efficiency allow, for the same products or services delivered, less resources (or exergy) to be used to drive the processes. This, in turn, leads to less extraction from the environment of energy resources, such as fossil fuels and uranium. Of course, a direct consequence of more efficient processes using fewer resources is that they normally emit less waste to the environment. Thus, problems like air pollution, liquid waste discharges and solid waste disposal are all somewhat mitigated when exergy methods are used to increase efficiency.

But the potential of exergy methods to assist in dealing with environmental impacts and issues goes deeper than just improved efficiency. This is not to say that efficiency improvement is not a useful and beneficial strategy for mitigating environmental impact. In fact, it certainly is. However, many other facets of exergy have environmental implications or linkages that can help us in understanding and addressing environmental concerns.

3.2. OTHER LINKAGES BETWEEN EXERGY AND THE ENVIRONMENT

Linkages between exergy and environmental issues have only recently begun to be addressed by the exergy community. So they are somewhat in their infancy and much effort needs to be devoted to their study if the full benefits of such linkages are to be exploited to address beneficially environmental concerns.

One important linkage is that exergy destruction due to irreversibilities is often related to chaos creation, or to the destruction of order, in organized systems. A pristine environment is quite ordered, with plants and animals often in abundance, and clean water, soil and air. The increase in disorder, or creation of chaos, associated with allowing pollutants to disperse randomly throughout the environment and the organization of living systems to be lost, certainly seems correlated to environmental impact. So, on a fundamental level, exergy appears tied to environmental impact.

I recall a conversation that I had over 25 years ago with David Scott, a colleague and friend who is most interested in elucidating clearly the importance of exergy. We extrapolated upon these ideas to speculate about whether the higher exergy of a clean and ordered environment is what makes it appealing to people, compared to a chaotic and polluted one. Could exergy be related to human values regarding the environment? Although we could not provide a rigorous proof to support this speculation, it was nonetheless fascinating to ponder.

A corollary of the ideas raised in the second previous paragraph is that the exergy destruction as a clean environment degrades to a chaotic one is a measure of the minimum work (or exergy) that is required to clean up, that is to reinstate the original condition of the environment. In fact, by considering the economic value of exergy in fuels, Gordon Reistad (1970) suggested an air-pollution rating in which the air-pollution cost for a fuel was estimated as either the cost to remove the pollutant, or the cost to society of the pollution (i.e., the tax which should be levied if pollutants are not removed from effluent streams). Reistad claimed the rating was preferable to the mainly empirical ratings then in use.

3.3. MORE RELATIONS LINKING EXERGY AND THE ENVIRONMENT

Another compelling linkage between exergy and the environment is that, since exergy represents a driving potential to do work or cause some change, exergy emitted without constraint into the environment probably represents a driving potential to cause change in the environment, or to impact upon it. Some of these ideas have also been elucidated elsewhere. For instance, Tadeusz Kotas (1995) writes, early on in his book on exergy methods, "*Quality of energy* is synonymous with its *capacity to cause change*." Further in the book he states, "In general the greater is the exergy of the pollutants, the greater is the disturbance of the equilibrium of the environment."

This idea is partly an outcome of the fact that exergy is evaluated with respect to a hypothetical reference environment, which is often taken to be a realistic model of the actual environment. A quantity has zero exergy when it is in equilibrium with the environment, and increases in exergy as its state deviates increasingly from the state of the environment. So, as a quantity becomes cooler or hotter, more pressurized or depressurized, more concentrated or dilute relative to the environment, its potential to impact on that environment increases.

This idea is certainly not yet fully developed by researchers and many aspects require further research. Exergy in itself cannot be shown rigorously to be equivalent to pollution, even though it exhibits characteristics that make it either a measure of potential for environmental impact, or a possible basis for such a measure. We do not know which types of exergy are most detrimental to the environment, based only on exergy values themselves, although we do expect chemical exergy usually to be the most potentially significant of all exergy components regarding environmental impact. But, while exergy does appear to correlate with some environmental impacts, it does not in any obvious way correlate with some others, such as which emissions cause health effects in humans and animals through, for example, toxicity. Much more thought is needed in this area. However, I feel that enough evidence exists to suggest that further valuable linkages exist between exergy and the environment and ecology and that these merit investigation.

An additional relation between exergy and the environment involves resources. Useful resources typically have exergy, by virtue of their being out of equilibrium with the environment. The degradation of resources that occurs when they are used or processed is directly measured by the corresponding exergy destruction. Thus exergy plays a role in understanding resource degradation. By corollary, exergy can also help improve understanding of the renewability and recyclability of resources.

3.4. Relations between Exergy and Ecology

Exergy is considered by many to be useful in understanding and managing ecological systems. Exergy provides a useful optic because ordered ecosystems have high exergy and disordered systems low exergy. Thermodynamics suggests that ecosystems seek to maximize exergy dissipation by maximizing internal exergy storage as biomass, biodiversity and complex trophical networks. Exergy has been used widely in ecological models and proposed as an indicator of ecosystem health or quality, as well as ecosystem development or change.

Human activity can decrease ecosystem exergy by decreasing biomass or internal complexity, and can convert ordered self-producing ecosystems and their resources into damaged and disordered or damaged ecosystems. For instance, exergy changes can help measure and assess the harm done when the energy and mineral resources, arable soils and clean waters of marine estuaries or forests are damaged or depleted.

3.5. Past and Present of Exergy, Environment and Ecology

The suggestion that exergy correlates in some ways with environmental impact is not new. Besides the work of Reistad mentioned earlier, Tribus and McIrvine (1971) suggest that 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. Also, Cambel (1980) repeated, in a special issue of *Energy—The International Journal*, a statement he first wrote in 1970: “The solution to the conflict between energy and the environment must not be in curtailing energy supply, but in reducing the irreversible and dissipative effects when we convert and consume energy.” Although this statement does not refer to exergy directly, its link to exergy is implicitly clear. In addition, Szargut (1980), an eminent and long-time exergy researcher, closed a 1980 paper reviewing international progress in the field of second law analysis by stating, "With the help of exergy it is … possible to establish an ecological economy for the purpose of saving natural resources."

Some relatively early works linking exergy with environmental impact and ecology were reported by Odum (1969), Jorgensen (1982), Edgerton (1982), Szargut et al. (1988) and Nielsen (1990). These early works laid the foundations for subsequent developments.

Many of the early ideas relating exergy and environmental impact were not well received by the established scientific and engineering communities, probably due to their newness and novelty. In fact, I am aware of some researchers who found it difficult to get the results of such research published or funded. But, it certainly seems like this state of affairs is changing, given the increasing activity and publications on exergy and environmental issues. Many investigations related to exergy, the environment and ecology bear this out:

- Frangopoulos and Von Spakovsky (1993) suggest an exergy- and economic-based approach, which they termed "environomics," for the analysis and optimization of energy systems, while accounting for environmental impact.
- Creyts and Carey (1997) propose the use of exergy analysis for assessing the environmental impact of industrial processes, while Makarytchev (1998) propose an exergy approach for evaluating environmental problems.
- Zhang and Reistad (1998) propose an exergy-based method for the evaluation of energy conversion systems, which includes global environmental aspects.
- Sciubba (1999) propose "an original approach to the evolution of the influence of environmental pollution reduction measures on the energetic balance of conversion processes and systems." He notes that the approach, which is based on exergy, synthesizes and extends the different approaches described in the above three points. Sciubba (2012) also assesses the use of an exergy-based ecological indicator as a measure of the resource use footprint, and Sciubba and Zullo (2011) demonstrate for sufficiently complex systems the existence of thresholds, below or beyond which the system is able to remain in a self-preserving condition (i.e., sustainable).
- Ayres et al. (1998) extendes exergy analysis to resource and waste accounting, and links the results using a life-cycle analysis (LCA) framework. LCA is an objective method for analyzing and improving the environmental impact of processes and systems, considering their full life cycles (Graedel and Allenby, 2010).

In addition, several exergy-based approaches to understanding and resolving environmental problems have been reported over the last decade in the *International Journal of Exergy* and its predecessor *Exergy, An International Journal*, as well as other publications:

- Wall (2003, 2010) and Wall and Gong (2001a, 2001b) discuss the relations between exergy and sustainable development, and analysis methods based on these relations.
- Connelly and Koshland (2001a, 2001b) discuss ties between exergy and industrial ecology, and propose exergy-based definitions and methods for addressing resource depletion. Industrial ecology is defined as "the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity,

given continued economic, cultural and technological evolution" (Graedel and Allenby, 2010).

- Rosen (2006) and Dincer and Rosen (2007) discuss the focus that exergy provides for issues involving energy, environmental and sustainable development.
- Berthiaume et al. (2001) apply exergy-based methods to evaluate the renewability of biofuels.
- Jorgensen (2012) has published an introduction to systems ecology that includes many exergy-based methods, while Pastres and Fath (2011) describe uses of exergy in ecosystems analysis and challenges.

3.6. Benefits and Needs

Despite the fact that some researchers question whether exergy is adequately related to environmental impact and ecology to form a useful tool, I feel that this area of research is of such significance and promise that there is likely a Nobel Prize waiting to be awarded to the researcher(s) who can discover the specific links between exergy and environmental and ecological impacts. Such information would be invaluable, as it would allow us to predict the environmental impacts of emissions and perhaps would allow us to know the dangers associated with new emissions, even before they are ever released to the environment, in part by evaluating their exergies. But for this hope to become reality, we need more research into the links between exergy, ecology and environmental impact, and into the potential applications and ways to exploit such linkages beneficially.

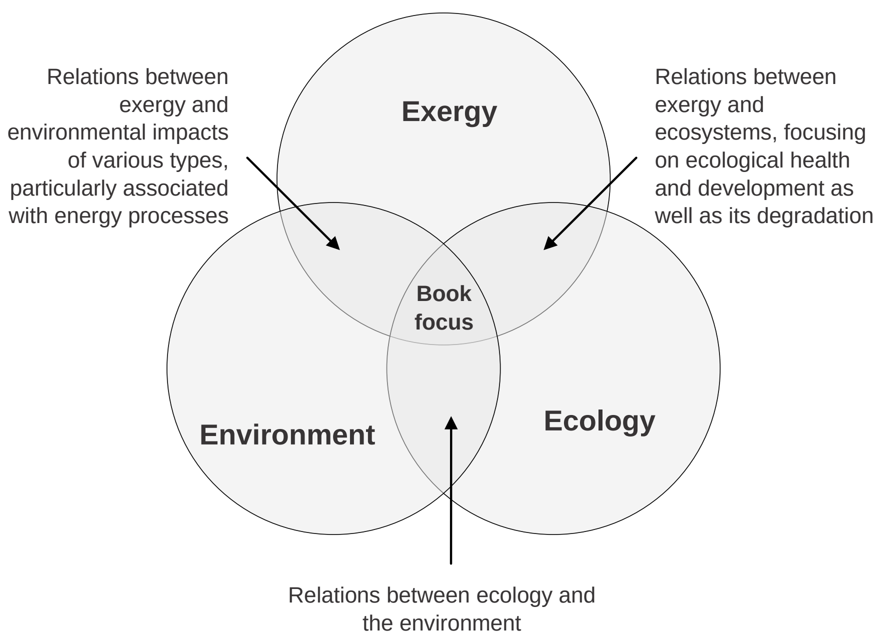

Figure 3.2. Illustration of how the combination of exergy, the environment and ecology form the focus of this book: an enhanced approach to environmental and ecological management.

3.7. Closing Remarks

Although a substantial amount of work on the relations of energy with the environment and ecology has been performed, advances in relating exergy with the environment and ecology are much less common. The latter field is introduced in this chapter, from the pioneering work in the 1960s and 1970s through to the present. A brief overview is presented of the linkages between exergy and environmental and ecological impact, and the corresponding methods that have been developed. These methods are based in part on the observations that the exergy in substance represents a potential to cause change and, if emitted to the environment in an unconstrained manner, can represent a potential to change ecosystems or the environment. The needs for further advances in and applications of exergy-based environmental and ecological relations are highlighted.

A summarizing diagram, illustrating how the combination of exergy, the environment and ecology form the focus of this book, an enhanced approach to environmental and ecological management, is presented in Figure 3.2.

Chapter 4

HISTORY OF EXERGY AND ENVIRONMENTAL AND ECOLOGICAL METHODS

OVERVIEW

The historical development of exergy-based concepts and methods related to environmental impact and ecology is presented, along with a broader historical overview of the history of exergy methods. The period covered spans more than two centuries, although the history of exergy-based environmental and ecological methods is limited to approximately the last 40 years. To complement the descriptions, many of the main contributors to the developments are identified. Based on the published literature, advances in exergy-based environmental and ecological methods appear to be occurring at an increasingly rapid pace, suggesting that future developments will be numerous.

This chapter describes the history of exergy-based environmental and ecological approaches and methods. To provide a broader context, this historical overview is complemented by a description of the history of exergy, which has its origins in the early 19^{th} century. Exergy-based environmental and ecological methods have developed somewhat in parallel to exergy methods, but are still in many ways in their infancy, having only begun to appear over the last four decades or so.

4.1. HISTORY OF EXERGY AND THE ENVIRONMENT AND ECOLOGY

This brief overview of the historical development of exergy-based environmental and ecological methods is provided because it is instructive to understanding the discipline. This treatment is intended to provide some key insights on developments and their timings, but does not provide a comprehensive historical review. Sciubba and Wall (2007) have provided good reviews of the historical evolution of exergy-based environmental and ecological methods, which are drawn on extensively in this section.

4.1.1. Exergy and the Environment

Physical costing using energy, material and environmental cost production factors represented in terms of exergy was proposed as early as the 1960s by Fratzscher, and extended by such researchers as Szargut, Wall, Grubbstroem and Sciubba.

Some of the first attempts to address environmental problems with exergy, by assessing the environmental impact of energy systems, are those by Kraft and Szargut.

Uses of exergy in resource management, including recovery and recycling, have appeared as early as the late 1970s.

The ideas that form the basis of cumulative exergy content were developed in the early 1970s, and the method itself was developed by Szargut in the late 1970s.

The inclusion of environmental externalities in exergy-economic methods was proposed in the 1980s and 1990s, e.g., Szargut (1980) and Frangopoulos and von Spakovsky (1993).

The use of exergy with life-cycle analysis to assess and address environmental issues was proposed in the 1990s by such researchers as Finnveden, Ostlund, Ayres, Cornelissen, Hirs, Dewulf and van Langehove. The enhancement of LCA by incorporating exergy and economics was proposed in the 1980s by van Gool and in the 1990s by several researchers. Subsequently, the underlying concept a life cycle perspective was incorporated in methods like thermoeconomics, cumulative exergy consumption and extended exergy accounting.

The use of exergy to understand and strive for sustainability began as early as the 1970s, before the coining of "sustainable development." Wall in 1977 described exergy a useful concept in resource management, for meeting the increasing needs of sustainable development. The use of exergy in sustainability is often an extension of the linkage of exergy and environmental factors, and seeks means of utilizing exergy in a practical manner to analyze environmental issues. Exergy-based approaches to sustainability have been considered by several researchers (Cornelissen, 1997; Cornelissen and Hirs, 2002). Cornelissen has also considered sustainability through a life cycle approach.

Subsequent work by Wall extended exergy methods to include natural resource accounting, life cycle exergy analysis, environmental indicators, and environmental taxation to encourage sustainable development.

The idea of extending exergy analysis to account for capital, labor and environmental factors stems from Grubbstroem. Further extensions were made to incorporate environmental measures with exergy-based economic ones by many researchers as well as others such as Enrico Sciubba. For instance, the extended exergy accounting method was developed by Sciubba (2001b) by utilizing exergy analysis and augmenting the cumulative exergy content of Szargut by exergy flows that represent the exergy equivalents of the capital, labor and environmental remediation.

The present author identified and described exergy-based environmental and economic relations in the 1980s. He also developed EXCEM analysis, in which designs are informed by flows exergy, cost, energy and mass.

Valero and colleagues coined the term exergoecology in 2002 for the analysis of environmental effects with exergy costing methods.

4.1.2. Exergy and Ecology

The analysis of ecological and biological systems with emergy, which somewhat relates to exergy, stems to the work of Odum (1969), and much research using emergy has been published since.

The analysis of ecological and biological systems with exergy appears to begin with the work of Jorgensen and Mejer in the 1970s. They propose exergy as an indicator for biological processes. Further refinements of the approach and applications of exergy to ecological and biological systems were made over the last two decades by many researchers, including Jizhong, Salomonsen, Jensen, Bastianoni, Marchettini, Marques, Xu, Fonseca, Ray, Debeljak, Demirel, Fabiano, Fath, and Cabezas.

Much research on the application of exergy to the modeling and analysis of ecological systems was undertaken in the late 1970s by such researchers as Jorgensen, Mejer, Eriksson and others. These efforts evaluate ecological health using exergy, while other approaches evaluate the ecological cost of pollution as the amount of exergy needed to remediate the effect of the pollution.

Research has also been carried out on complex structures that interact with the biosphere (Nielsen, 1995, 1997; Bendoricchio and Jorgensen, 1997; Szargut, 2005).

4.1.3. Predicting the Future from the Past

The literature on exergy-based environmental and ecological methods has grown dramatically in recent years, extending the many significant techniques that have been proposed in the past. Important exergy-based environmental and ecological techniques from the past and present are discussed in this book. From these discussions of past developments, some predictions on the future can be made.

Numerous issues related to exergy and ecology and the environment need to be addressed, ranging from fundamental understanding to applications in tools (e.g., life cycle analysis, resource management, the design of production cycles using exergy concepts, and sustainability). The connections of exergy with environmental and ecological issues also need to be further investigated, and methods for the analysis of ecosystems and other living systems with exergy will likely continue to be developed.

Environmental considerations will likely be incorporated in some form into exergy-based economic methods, and such methods will be increasingly adopted in the assessment of industrial processes. Thermoeconomics, cumulative exergy content and extended exergy accounting will likely be increasingly applied in the future. Exergy-based optimization procedures that link exergy, ecology and the environment will likely be enhanced and new ones developed. Other future developments may include the development of techniques for system synthesis, where process configuration is determined, and the use of genetic algorithms and artificial intelligence techniques to link exergy, the environment and ecology.

4.2. History of Exergy

In this section, a brief overview is provided of exergy's historical roots and development, drawing heavily on previous reports (Rezac et al., 2004; Rezac and Metghalchi, 2004; Kotas, 1995; Sciubba and Wall, 2007). This material is intended to be explanatory and to help make exergy more widely understood by describing its foundations. Since the commodity that is sought because it can drive processes and devices is not *energy*, but rather *exergy*, it is exergy that engineers and scientists strive to deliver. Exergy analysis, because of its origins in the second law of thermodynamics, can help society gain the greatest possible benefit from its resources and operations. In fact, some propose that energy policy be based on exergy methods (Rosen and Dincer, 2002).

Although exergy analysis is a relatively new tool, its origins can be traced back nearly two hundred years. The infancy of second law analysis in the early nineteenth century was Carnot's idea of maximum work and the concept of entropy (Lambert, 2011).

4.2.1. The Early Years

Maximum Work: Carnot (1824) and Clapeyron (1834)

The main impetus for exergy analysis was provided in 1824 when Sadi Carnot published "Reflections on the Motive Power of Fire and on Machines Fitted to Develop that Power" (Carnot et al., 1977). The world was then undergoing great change, with the materials that fueled the industrial revolution in huge demand and steam engines, invented about a century earlier, needed in great numbers to power new technologies. Carnot, a Frenchman, saw the advantages England had gained as a result of its advances in steam engines, and he realized that his own country would have to take similar strides if it wished to catch up.

To this point, advances in steam engines were accomplished mainly through trial and error. Although great mechanical skills were dedicated to the task of creating better, more efficient engines, the field of engine efficiency lacked a sound theoretical background and many misconceptions about the relations between heat and work permeated scientific thinking. Under a French environment that was pervaded by many of these false assumptions, Carnot, basing his analysis on the impossibility of perpetual motion, was able develop the closed cycle of operations and understand that the ability of a system to perform work had to do not so much with its energy, but rather with its deviation from equilibrium. Using this treatment, Carnot was able to estimate the maximum theoretical work that could be accomplished by a steam engine utilizing a certain amount of coal as fuel. Carnot was further able to recognize that this quantity was dependent only on the quantity of energy transferred via heat interactions, and the temperatures of the two bodies between which the energy passed. Though many of Carnot's equations were incorrect, his treatment was such a breakthrough that to this day the efficiency of heat engines is usually rated by comparison to a perfectly reversible machine called the Carnot engine.

Carnot's work was not widely published and remained relatively obscure. It was not until 1834, after Carnot's death, that a fellow Frenchman, Emile Clapeyron, reformulated much of Carnot's work and published his "Memoir on the Motive Power of Heat" (Carnot et al., 1977). This paper was more analytical in nature than Carnot's and most of its equations stand to this day as correct. This paper was more widely published and eventually translated into German, allowing Carnot's results to become known to physicists of the day, who further advanced, refined and explained them.

Entropy: Clausius (1850)

In 1850, the German physicist and chemist Rudolf Clausius re-examined Carnot's and Clapeyron's results, in light of his treatment of the equivalence between work and heat, and published "On the Motive Power of Heat" (Carnot et al., 1977). Clausius later defined entropy and stated that the entropy of the universe cannot decrease. This allowed Carnot's results to be seen as a consequence of the first and second laws, implying that in any process energy is conserved and entropy increases. At this time, the idea that an energy source could perform some finite quantity of maximum work, with which Carnot began, could be proven by analyzing a system with respect to the first and second laws.

Available Energy of Body and Medium: Gibbs (1873-1878)

Still lacking at this time was a means for determining maximum work for general purposes. In the 1870s, Josiah Willard Gibbs published three significant works in thermodynamics, one describing dissipated energy (Gibbs, 1961). Gibbs also considered the maximum amount of mechanical work that can be accomplished by a given body without a net heat transfer or volume change. He called this quantity the available energy of the body and described how it can be determined. It is noted that Gibbs' available energy is analogous to what Gyftopoulos and Beretta (1991) more recently called adiabatic availability.

Gibbs went on to expand his idea of available energy to "approach more nearly the economical problems which actually present themselves, if we suppose the body to be surrounded by a medium of constant pressure and temperature, and let the body and medium together take the place of the body in the preceding problems." Gibbs called this quantity the available energy of body and medium.

In "On the Equilibrium of Heterogeneous Substances," Gibbs resolved some remaining issues concerning chemical potential, and gave a definition for exergy when he wrote, "We will first observe that an expression of the form

$$-e+T\eta-Pv+M_1m_1+M_2m_2...+M_nm_n \tag{4.1}$$

denotes the work obtainable by the formation (by a reversible process) of a body of which e, η, v, m_1, m_2, … m_n are the energy, entropy, volume, and the quantities of the components, within a medium having the pressure P, the temperature T, and the potentials M_1, M_2, …M_n." This Gibbs' notation is utilized in this quotation.

Gibbs' works provide a foundation for modern exergy or second law analysis methods.

Usable Energy: Gouy (1889) and Stodola (1898)

Physicist Louis Gouy's 1889 publication, "On Utilizable Energy" in the *Journal de Physique*, and mechanical engineer Aurel Stodola's independent work on "free technical energy" advanced the concepts further, with Gouy's work considered by many to denote the birth of available energy. Somewhat later, the "Gouy-Stodola theorem" was coined, which states that exergy loss is entropy production multiplied by the temperature of the surroundings and indicates that minimizing exergy loss is equivalent to minimizing entropy production due to irreversibilities.

Generalization and Methodology: Keenan (1951)

Joseph Keenan **(**1951) published an article entitled “Availability and Irreversibility in Thermodynamics,” noting the lack of generality of some methods and noting that Gibbs’ treatment had a more general basis. Keenan relies on the second law and Gibbs’ findings to obtain expressions for maximum work, and develops expressions for the availability of several types of systems, quantifiable irreversibility and coefficients of performance.

Keenan concludes his paper with the following statements: “Quantitative concepts of maximum useful work, availability, irreversibility, and quality of performance of a thermodynamic task may be defined from consideration of the first and second laws of thermodynamics for all processes between equilibrium states of a system operating within an infinite stable atmosphere. These concepts may be extended to cover flow across a control surface and, as a more special case, to steady flow through a control surface. They may be applied to as wide a range of processes and as great a variety of systems as the science of thermodynamics itself” (Keenan, 1951). This paper, and some of Keenan’s other works, provide examples and methods for extending Gibbs’ findings to all areas of thermodynamic interest, without losing generality. This allowed second law analysis to be accurately applied to a vast new range of real systems, greatly adding to its utility.

Other Early Developments

The main steps in the historical development of exergy have been discussed in this section, but there have been many others. For instance, Grassmann contributed to exergy methods, and as a consequence exergy flow diagrams of processes are now referred to as Grassmann diagrams. Furthermore, numerous advances had been made in applying expressions for maximum work to specific cases by James Clerk Maxwell (1891), Georges Darrieus (1930), Fran Bosnjakovic (1930s) and others, but their methods are not discussed here since they were restrictive and lacked generality. Shannon (1948) provided a mathematical theory of communication using the second law.

4.2.2. Towards Maturity

Since Keenan’s work, exergy analysis was coined as a term, and the method has been applied to many different fields, primarily as a tool for thermodynamic assessment, optimization and design and for energy management.

Exergy: Rant (1956)

Shortly after Keenan’s publication, the scientist Zoran Rant (1956) published an article introducing the term exergy (written exergie in German) to connote the reversible work accomplished through a cyclic process in which heat passes from temperature T to the environment temperature T_0. Rant created the term exergy by combining the Greek *exo* meaning out, and *energeia* meaning energy, with a slight modification made to make the word more closely resemble energy (*energie* in German).

About 50 years were to pass before Rant's term exergy become globally accepted and relatively standard vernacular. In the interim, terms such as availability, available energy, available work and essergy were used by many and some are occasionally still used today, although in such instances they are generally interchangeable with exergy.

Alternative Definition of Exergy and Anergy: Baehr (1965)

A German, Hans D. Baehr, generally defined exergy in 1965 by writing, "Exergy is the totally convertible part of the energy, i.e., that part which may be converted into any other energy form" (Wall, 1986). Baehr's definition implies that the energy of a system has two parts: exergy, which is the convertible part, and anergy, the non-convertible part. This definition is sometimes misleading because energy does not always divide in this manner.

Baehr further discussed anergy (the non-convertible part of energy) during the 1960s and, although not commonly applied, it has been used even in recent years.

Expansion of Interest

Exergy became increasingly of interest starting in the 1970s, leading to a rapid expansion in its development and application. This interest is in part demonstrated by the observation that the number of articles on exergy published in journals or presented at conferences increased from about 50 in 1970 to over 500 in 2004 (Sciubba and Wall, 2007). The rapid increase in noteworthy developments and applications of exergy in the 1970s was fostered in part by the "energy crises" of 1973 and 1978 due to OPEC oil embargos, which raised significantly government and industry interest in efficiency, but it also likely was motivated by the increasingly clear presentations of exergy that were being published prior to that period. For instance, in the early 1960s, MIT professor Myron Tribus discussed the value of the concept of exergy in one of his courses.

The use of exergy audits, in place of energy audits, was proposed as early as 1977 by Richard Gaggioli. Furthermore, the idea of assessing and responding to the "energy crises" of the 1970s using exergy methods was proposed by Dehlin in 1979, and resulted in related work in subsequent years.

The idea of identifying malfunctions in a component or system by examining the impact on the exergy efficiency of connected components was suggested by Buergel in the 1970s, and methods for such diagnosing were developed in the last decade or so by researchers such as Valero and Torres.

Societal systems, like regions and countries, were first assessed with exergy by Reistad (1975), who examined the U.S. The method was extended subsequently.

Maturity

Exergy as a concept and tool appears to have reached maturity, in its role of assessing and improving efficiency, roughly in the 1990s (Sciubba and Wall, 2007). Beyond being increasingly recognized as a mature field, exergy analysis is beginning to be regarded as a standard industrial procedure. Exergy methods now allow engineers, scientists and others to analyze resource utilization and efficiency much more effectively than energy analysis alone.

Exergy and exergy-based economics have matured to the point where, in 2004, the *International Journal of Exergy* was launched by Inderscience Publishers (www.inderscience.

com). This carried on from the publication by Elsevier of *Exergy, An International Journal* from 2001-02.

Furthermore, advanced tools have developed subsequently, e.g., the use of exergy with artificial intelligence has begun over the last decade.

4.3. Developments of Related Disciplines

Major advances continue to be achieved through the extension of exergy analysis beyond the realm of thermodynamics into such areas as exergy-related economics and economic resource theory, information theory and environmental impact prediction.

4.3.1. Exergy, Environment and Ecology

As described in Section 4.1 and throughout this book, significant advances continue to be achieved through extending exergy analysis into the areas as the environment and ecology.

4.3.2. Exergy and Economics

An entire field of exergy-based economics spawned from developments in exergy analysis. A non-comprehensive review of the development of this field is provided here, focusing on some key developments. Çolpan (2005) and Sciubba and Wall (2007) have provided good reviews, which are drawn on in this section, of the historical evolution of exergy-based economic methods.

The linking of costing with thermodynamics, especially entropy or related considerations, was explored almost a century ago, e.g., in the 1920s by Lotka, the 1930s by Keenan, the 1940s by Benedict and the 1950s by Gilbert (Sciubba and Wall, 2007). For instance, the allocation of costs among cogeneration products (steam and power) using exergy was discussed as early as the 1950s by such researchers as Beckmann, Henatsch and Szargut.

The term exergoeconomics came about in that period. Advanced methods like structural thermoeconomics followed in subsequent decades, e.g., by researchers such as Valero.

Articles referring to the economic value of the concept of exergy began to appear in the literature in the late 1950s and 1960s. Researchers such as Wolfgang Fratscher, Jan Szargut, Valeriy Brodyanskii, Myron Tribus, Yehia El-Sayed and Robert Evans were among the early developers of what was then a new field, stemming from the integration of exergy and economics. The term thermoeconomics appeared in 1960 in the course notes of Tribus at MIT and in 1961 in the doctoral thesis of Evans. Tribus, El-Sayed and Evans published a series of articles on a mathematical cost-optimization procedure based on exergy (called availability by them at that time), such as Evans and Tribus (1962), and El-Sayed and Evans (1970).

The concept was further developed through research by Yehia El-Sayed, Richard Gaggioli, Tadeusz Kotas and Michael Moran in the 1970s and 1980s. Adrian Bejan, Antonio Valero and George Tsatsaronis also began making notable contributions to the field in the 1980s. For instance, Thermoeconomic Functional Analysis, an optimization methodology that provides marginal costs, was proposed by El-Sayed and Evans around 1970, and further developed by such researchers as El-Sayed and Tribus through the 1980s, Christos Frangopoulos in the 1980s and 1990s and by Michael von Spakovsky and Evans in the 1990s. Also, exergetic cost theory, a cost accounting method that provides average costs, was introduced by Tsatsaronis and Winhold in 1985. A general and formalized costing theory to calculate the exergy cost of a product from the exergy input to the process and the structure of the process was developed by Valero in a series of articles published in the late 1980s.

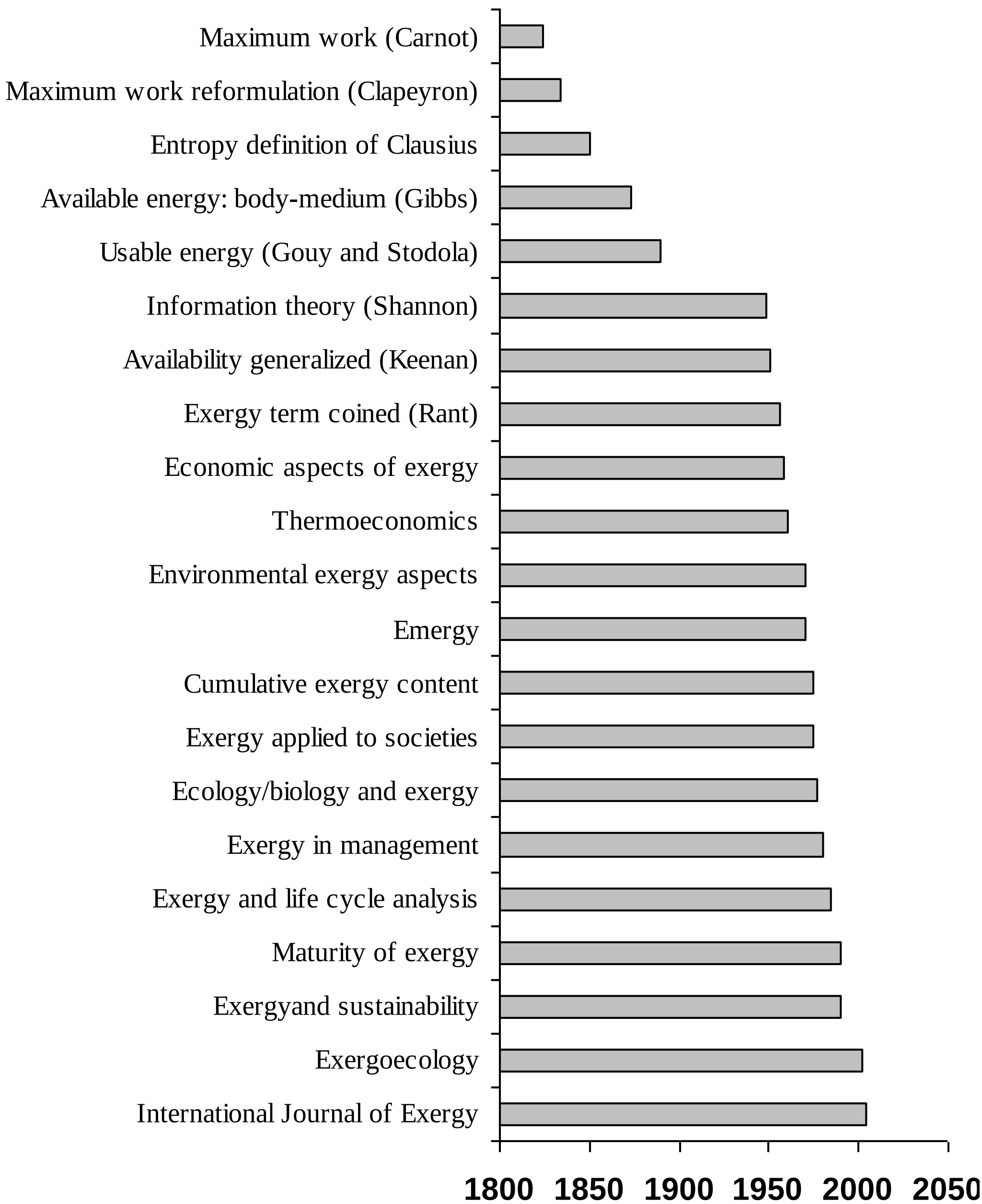

Figure 4.1. Selected historical developments in exergy and exergy-based environmental and ecological works, starting with the developments and advances in thermodynamics in the early 19th century.

The present author developed two exergy-based economic methods in the 1980s: EXCEM analysis and loss-cost ratio analysis, in which designs are informed by the ratio of thermodynamic loss (based on exergy) to capital cost. Efforts by Szargut et al. (1988) to include taxation effects into pricing structures enhanced thermoeconomics.

Extensions to the field of exergy and economics were made in the 1990s. For instance, Frangopoulos and von Spakovsky adapted thermoeconomics to off-design conditions and time-dependent problems. Also, the SPECO (specific exergy costing) method was proposed by Tsatsaronis and Lin in 1990, and then further developed by Tsatsaronis and his colleagues. Further extensions were made to incorporate environmental measures by these researchers as well as others such as Enrico Sciubba, Giampolo Manfrida and Andrea Lazzaretto.

The literature on thermoeconomics has grown dramatically in recent years, extending the many significant exergy-based economic techniques that have been proposed in the past, including thermoeconomic functional analysis and the exergetic cost theory, and proposing new ones. Important exergy-based economic techniques from the past and present are discussed by this author in another book (Rosen, 2011).

4.4. Closing Remarks

The historical development of exergy-based environmental and ecological methods presented in this chapter describes the many advances made over the past 40 years or so through the efforts of many great engineers and scientists. Descriptions of the broader advances made in exergy analysis over the past couple centuries provide a context for the discussions of exergy-based environmental and ecological methods. This can be seen in Figure 4.1, where selected historical developments in exergy and exergy-based environmental and ecological methods are summarized. Exergy, and its specific use in environmental and ecological fields, can be observed to have advanced along with society, responding to changing societal needs and technology developments. Work continues on improving exergy-based environmental and ecological methodologies, which in many ways are still in their infancy, and on expanding applications. Future advances are likely to benefit people, communities, industry and society.

PART II:
CONCEPTS AND METHODS

Chapter 5

EXERGY

OVERVIEW

Exergy and its use in exergy analysis is described, including basic principles and implications. Energy and exergy methods are contrasted, and weaknesses in energy assessments that exergy approaches overcome are pointed out. It is shown that exergy provides a measure of usefulness or quality, efficiencies that truly measure approach to ideality and clarity on the limitations imposed on system or process performance.

This chapter describes exergy and exergy analysis, as well as a procedure for exergy analysis. Aspects of thermodynamics relevant to exergy analysis are discussed, as are exergy principles, quantities, efficiencies, implications and benefits.

5.1. EXERGY ANALYSIS AND THE PROBLEM WITH ENERGY ANALYSIS

Thermodynamics permits the performance and efficiency of energy systems to be described. Conventional thermodynamic analysis is based primarily on the conservation of energy principle embodied in the first law of thermodynamics. An energy analysis of a process or system essentially accounts for the energy exiting (with products and wastes) and entering. Efficiencies usually evaluated as energy ratios are conventionally used to evaluate and compare processes and systems.

But energy efficiencies do not always assess how nearly performance approaches ideality and are consequently often misleading. Also, factors which cause performance to deviate from ideality (i.e., thermodynamic losses) are often not properly described qualitatively and quantitatively with energy analysis. For example, energy analysis can locate the principal inefficiencies wrongly in a system and assess a state of technological efficiency different than actually exists. Another approach is needed which circumvents these concerns, and that is where exergy analysis comes into play.

Exergy analysis, a thermodynamic analysis technique based on the second law of thermodynamics, overcomes many of the shortcomings of energy analysis. Exergy analysis gives efficiencies which provide a true measure of how nearly actual performance approaches ideality, and identifies properly the causes, locations and magnitudes of inefficiencies.

Exergy analysis quantitatively indicates

- the theoretical limitations imposed on a system, which show that a real system cannot conserve exergy and that only a portion of the input exergy can be recovered, and
- practical limitations by evaluating losses which directly measure lost exergy.

By providing an illuminating, rational method for meaningfully assessing and comparing systems and processes, exergy analysis can assist in improving and optimizing designs.

Exergy analysis is described extensively elsewhere (e.g., Dincer and Rosen, 2007; Rosen, 1999; Gaggioli, 1983; Moran et al., 2011; Kestin, 1980; Moran, 1989; Moran and Sciubba, (1994; Kotas, 1995; Bejan, 2001; Feidt, 2009; Borel and Favrat, 2010).

5.2. Procedure for Energy and Exergy Analyses

A simple procedure for performing energy and exergy analyses of a process or system involves the following steps, which are elaborated upon in subsequent subsections:

- Separate the process or system into as many sections as desired so as to achieve the depth of detail and understanding desired.
- Determine all basic quantities (e.g., work, heat) and properties (e.g., temperature, pressure).
- Perform mass and energy balances.
- Select an appropriate reference-environment model, accounting for the nature of the process, the acceptable accuracy, the acceptable analysis complexity, and the questions being investigated.
- Evaluate energy and exergy values, relative to the selected reference-environment.
- Perform exergy balances, and determine exergy consumptions.
- Evaluate efficiencies, taking into account the desired measure of merit in selecting the efficiency.
- Draw appropriate interpretations, conclusions and recommendations from the results, addressing as appropriate design changes, retrofit plant modifications, etc.

The steps in the procedure for energy and exergy analyses of a process or system are shown in Figure 5.1, spanning basic steps through outcomes.

5.3. Energy and Exergy Balances

A balance for a quantity in a system states that the accumulation of the quantity is the sum of the input and generation less the output and consumption.

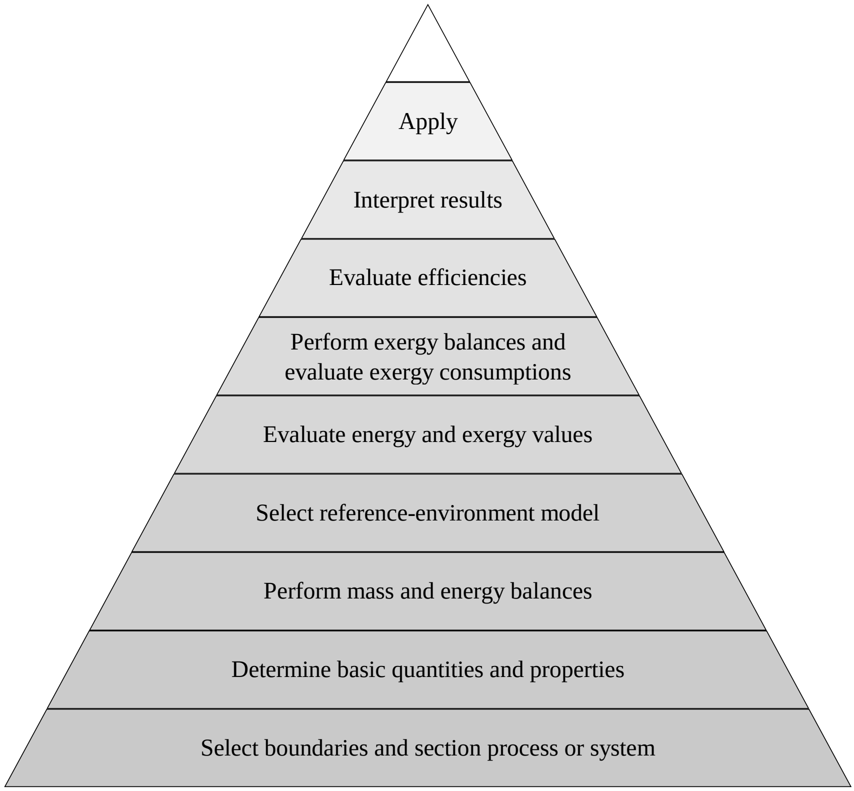

Figure 5.1. Steps in the procedure for energy and exergy analyses of a process or system, starting with basic steps at the foundation and culminating with outcomes at the apex.

Input and output refer respectively to quantities entering and exiting across system boundaries, while generation and consumption refer respectively to quantities produced and consumed in the system. Accumulation refers to build-up (either positive or negative) in the system of the quantity.

This general balance may be written for energy and exergy, as well as other quantities.

Energy, being conserved (neglecting nuclear reactions), can be neither generated nor consumed. Consequently, an energy balance can be written as

$$\text{Energy input} - \text{Energy output} = \text{Energy accumulation} \tag{5.1}$$

The output term in this balance can be separated into product and waste components:

$$\text{Energy output} = \text{Product energy output} + \text{Waste energy output} \tag{5.2}$$

Exergy is consumed due to non-idealities, in proportion to the entropy creation due to irreversibilities. Therefore, a corresponding exergy balance can be expressed as

$$\text{Exergy input} - \text{Exergy output} - \text{Exergy consumption} = \text{Exergy accumulation} \tag{5.3}$$

As with energy, the exergy output can be divided into product and waste terms:

Exergy output = Product exergy output + Waste exergy output (5.4)

The exergy balance is a combination of the conservation law for energy and non-conservation law for entropy. Exergy consumption can also be expressed as the difference between the total exergy flows into and out of the system, less the exergy accumulation in the system. A key difference between energy and exergy is seen with these balances: exergy, a measure of energy quality or work potential, can be consumed, but energy is conserved.

For a cyclic process with identical initial and final states, the accumulation terms in the balances are zero.

5.4. Exergy and Exergy Quantities

The exergy of an energy or material quantity is a measure of its usefulness or quality. Technically, exergy is the maximum work obtainable from an energy or a material quantity as it passes reversibly to the environmental state, exchanging heat and materials only with the surroundings (Gaggioli, 1998; Kestin, 1980; Gaggioli and Petit, 1977; Szargut, 1980).

The units of exergy are the same as those of energy, but while energy focuses on quantity, exergy focuses on quality. Since energy can be degraded in quality even though energy is conserved in quantity, exergy is not conserved for real processes.

For a process, the input exergy is a measure of the maximum potential associated with the input material and energy. This maximum is retained and recovered only if the inputs undergo processes reversibly. No further useful exergy can be extracted by allowing a system and its environment to interact if they are in equilibrium. Losses in the potential for exergy recovery occur in the real world because actual processes are always irreversible.

This point highlights the fact that, although energy cannot be created or destroyed, exergy (or energy quality) can be degraded, eventually reaching complete equilibrium with the surroundings and becoming of no further use for performing tasks.

Both energy and material quantities possess exergy:

- Non-material quantities. The exergy associated with shaft work, based on the definition of exergy, is equal to the energy. Similarly, the exergy associated with electricity is equal to the energy. The exergy associated with a heat transfer, or the thermal exergy, is a function of the temperature at which the heat transfer occurs.
- Material quantities. The exergy of a system containing material can be expressed as the sum of the physical, chemical, kinetic, potential and other exergy terms. The exergy depends on the properties of the material and of the reference-environment, combining the system's extensive properties with the reference-environment's intensive properties. Similarly, the exergy of a flowing stream of matter is the sum of the exergy of a system containing matter plus the exergy associated with the flow work of the stream.

A breakdown of exergy quantities into material and non-material types is shown Figure 5.2.

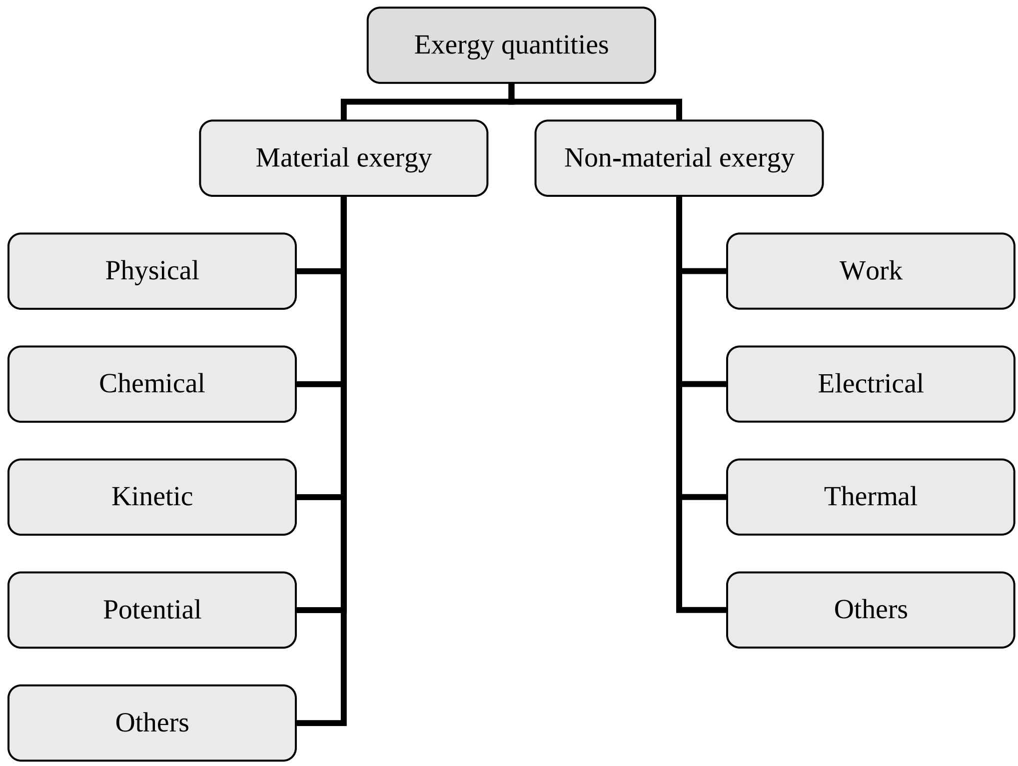

Figure 5.2. Breakdown of exergy quantities into material and non-material types. Components of material exergy are shown.

The exergy *Ex* of the matter contained in a system may be written as

$$Ex = S(T - T_o) - V(P - P_o) + n_k(\mu_k - \mu_{ko}) \tag{5.5}$$

where the intensive properties are temperature T, pressure P, and chemical potential of substance k, μ_k; and the extensive properties are entropy S, volume V, and number of moles of substance k, n_k. The subscript "o" denotes conditions of the reference environment, with respect to which exergy is calculated. The term on the far right of the above equation can be evaluated by summing over all chemical constituents when more than one is present.

5.5. THE REFERENCE ENVIRONMENT

Since exergy is evaluated with respect to a reference environment, its intensive properties partly determine the exergy of a flow or system. The reference environment used in exergy calculations is normally characterized by specifying its temperature T_o, pressure P_o and chemical potential μ_{ko} for each of its k constituents. It is seen in Equation (5.5) that the exergy of a system is zero when it is in equilibrium with the reference environment because $T = T_o$, $P = P_o$ and $\mu_k = \mu_{ko}$ for all k.

The reference environment is in theory in stable equilibrium, with a constant intensive state (temperature, pressure, chemical potentials) and all parts at rest relative to one another. The reference environment acts as an infinite system, and is a sink and source for heat and materials, but chemical reactions do not occur between the environmental components. The exergy of a flow or system in equilibrium with the reference environment is zero.

The reference environment as an element of exergy analysis, its characteristics, and its role relating exergy to environmental and ecological assessments, are discussed in depth in the next chapter.

5.6. Exergy-Based Efficiencies

Efficiency is an important factor in decisions regarding resource utilization. Many have examined efficiencies and other performance measures (Sussman, 1981).

Efficiency is defined as "the ability to produce a desired effect without waste of, or with minimum use of, energy, time, resources, etc.," and commonly means the effectiveness with which resources are used to do or make something, or the degree to which the ideal is approached in such activities.

For general engineering systems, efficiencies are typically ratios of appropriate quantities. For energy-intensive and energy-conversion systems, efficiencies are conventionally energy ratios. A process then has maximum efficiency if energy input equals recoverable energy output or if no "energy losses" occur. However, such efficiencies do not measure "approach to ideality" and so are misleading.

More meaningful efficiencies require a quantity for which ratios can measure approach to ideality. The second law must be invoked as it states that ideality is attained for a reversible process, but this law must be quantified first. Although this can be done with entropy, it is difficult to create efficiency measures using entropy.

Alternatively, meaningful efficiencies are obtained with ratios based on exergy, and maximum efficiency is attained for a process which conserves exergy. Exergy efficiencies clearly measure approach to an ideal.

Gaggioli (1983) calls exergy efficiencies "real" or "true" efficiencies, while calling energy efficiencies approximations to real efficiencies. Some significant benefits of exergy efficiencies are that they:

- provide more illuminating insights into efficiency than energy efficiencies because they weigh energy flows according to their exergy contents and separate inefficiencies into effluent losses and irreversibilities,
- provide a measure of potential for improvement,
- are always between 0% and 100%, and are thus more intuitive than energy efficiencies, and
- clarify measures that can exceed 100% when energy is considered, like coefficient of performance, as such measures are between 0% and 100% based on exergy.

There exist several exergy-based efficiencies. A common energy efficiency η for processes and systems is

$$\eta = \frac{\text{Energy in product outputs}}{\text{Energy in inputs}} = 1 - \frac{\text{Energy loss}}{\text{Energy in inputs}} \tag{5.6}$$

The corresponding exergy efficiency ψ is

$$\psi = \frac{\text{Exergy in product outputs}}{\text{Exergy in inputs}} = \frac{\text{Exergy loss plus consumption}}{\text{Exergy in inputs}} \tag{5.7}$$

5.7. Implications, Benefits and Recognition of Exergy Analysis

Exergy analyses of systems impact application decisions and research directions. In the latter case, exergy analyses provide insights into the "best" directions for research, more than energy analyses, where "best" means the most promising for significant efficiency gains. Two primary reasons for this observation follow:

- Exergy losses represent true losses of the potential to generate the desired product from the input. Energy losses do not. To increase efficiency while accounting for energy degradation, addressing exergy losses focuses research on reducing losses that impact the objective.
- Exergy efficiencies always measure how nearly a process or system approaches the theoretical upper limit. Energy efficiencies do not. By focusing research on sections or processes with low exergy efficiencies, effort is directed where the largest margins for efficiency improvement inherently exist, whereas focusing on energy efficiencies can target areas with little margins for improvement, even theoretically.

Application and research decisions must account for economic, environmental, safety, social, political and other factors, in addition to energy and exergy. The latter inform beneficially such decision making, and suggest from a thermodynamic view that exergy analyses typically find that improvement efforts should concentrate more on internal rather than external exergy losses, with a higher priority for the processes having larger exergy losses. Of course, research should also address processes having low exergy losses where cost-effective improvement measures are identified.

Increasing application and recognition of the usefulness of exergy methods by those in industry, government and academia has been observed in recent years (Moran, 1989; Kotas, 1995; Edgerton, 1982; Szargut et al., 1988). Exergy methods have even been suggested as an aid for energy planning and policy development (Rosen, 2002c; Rosen et al., 2008).

The significance of exergy has been described well by Sciubba (2001a), who notes that energy conversion systems were subject to assessment based on second law concepts over five decades ago. He wrote, "relevant design procedures of the time neglected to recognize that the irreversibility in processes and components depend on the energy "degradation rate" and not only on the ratio between the intensities of the output and input flows, and that there is a scale of energy quality that can be quantified by an entropy analysis." The legacy of this early work, which led in part to the development of exergy analysis, is that efficiencies based solely on energy and the first law are increasingly recognized as at best misleading and often erroneous. Sciubba further notes that exergy analysis "has had a very profound impact on the energy conversion system community, to a point that it is difficult today to find a design standard which does not make direct or indirect use of exergetic concepts in its search for an 'optimal' configuration."

Because of the growing acceptance of exergy, books on exergy and related methods have been written (Bejan, 1982; Kotas, 1995; Moran, 1989; Szargut, 2005; Szargut et al., 1988; Brodyanski et al., 1994; Sato, 2005; Dincer and Rosen, 2007) and general thermodynamics texts have increasingly included exergy (Bejan, 2006; Moran et al., 2011).

5.8. The Rebound Effect

Efficiency improvement measures and policies, whether based on energy or exergy, usually aim to reduce energy resource utilization and associated carbon emissions and other forms of environmental impact. However, increased efficiency can reduce the unit price of energy (or exergy) services which, in turn, can inadvertently cause the use of these services to increase. This "rebound effect" (Holm and Englund, 2009; Madlener and Alcott, 2009; Sorrell et al., 2009) can partially or fully offset the benefit of the efficiency increase. The magnitude of such effects is an important factor in determining whether or not improved efficiency should be a strategy for environmental or ecological policy. An exergy perspective can be taken of the rebound effect (Madlener and Alcott, 2009).

Empirical estimates of the direct rebound effect have been reviewed (Sorrell et al., 2009), along with relevant theoretical and methodological issues. The direct rebound effect is usually less than 30% for household energy services in the OECD, but various potential sources of bias exist that may lead to overestimations of the rebound effect. For many energy end uses, the size of the rebound effect for energy efficiency improvements is observed to vary from about 5 to 15%. Rebound effects are sensitive to energy-service price elasticities, and are often high when energy efficiency improvements have small (or negative) capital costs. Furthermore, the rebound effect for increases in ecoefficiency has been investigated for the United States and several western European countries for 1960-2002 (Holm and Englund, 2009). The discrepancy between the potential and actual decrease of use of natural resources due to increased efficiency was found to be more prominent in the U.S. than for European countries. This knowledge can help efforts to reduce exergy, energy and material utilization and their harmful effects on the biosphere, and to establish appropriate economic policies.

Madlener and Alcott (2009) have summarized discussions of the rebound effect from an economic growth perspective and provided useful understanding and insights. Of course, environmental or energy policies strategies may increase economic growth, affluence and living standards even if environmental or energy policies do not achieve their full potential due to the rebound effect.

5.9. CLOSING REMARKS

Exergy is described as is the tool derived from it, exergy analysis. Principles and implications are explained, differences between energy and exergy methods are highlighted, and deficiencies of energy methods that can be overcome using exergy are discussed. An exergy analysis procedure is described. The manner is explained by which exergy, a measure of usefulness or quality, quantifies efficiencies that measure approach to ideality and the theoretical and practical limitations imposed on a system or process.

Chapter 6

SUITABLE REFERENCE ENVIRONMENTS FOR ENVIRONMENTAL AND ECOLOGICAL ASSESSMENTS

OVERVIEW

The reference environment is a hypothetical system that may or may not mimic the natural environment. When the natural environment simulates the reference environment, exergy quantities can extend beyond thermodynamic losses to exergy efficiencies and, of notable significance, the potential for environmental and ecological impact. Extending the reference environment to the natural environment is important to exergy-based environmental and ecological management. An appreciation of the sensitivity of exergy quantities to variations in the reference environment is also important.

The reference environment described in the previous chapter may or may not relate to the actual or natural environment. When there is a good similarity between the reference and natural environments, exergy analyses can be used to assess not just thermodynamic losses, but also exergy efficiencies and, potentially, environmental impacts. For instance, a realistic reference environment model potentially allows a quantification of the environmental and ecological impact of emissions. Extending the reference environment to the natural environment is consequently a key link in enhancing the ability of exergy analysis to assess and improve environmental and ecological systems.

This section describes the reference environment used in exergy analysis, as well as its characteristics and models. The linkage of the reference environment to the natural environment is also described to identify suitable reference environment models for environmental and ecological assessments. The sensitivity of exergy quantities to variations in the properties of and models for the reference environment are assessed, to gauge how significant the choice of a reference-environment model and its properties is to exergy analyses in general and exergy-based environmental and ecological assessments in particular.

6.1. THE REFERENCE ENVIRONMENT IN EXERGY ANALYSIS

As pointed out in Section 5.5, the reference environment used in exergy calculations is normally characterized by specifying the following intensive properties for it:

- temperature T_o
- pressure P_o
- chemical potential μ_{ko} for each of its k constituents.

The reference environment is hypothetical and has several significant theoretical characteristics. Specifically, the reference environment:

- is in stable equilibrium.
- has a constant intensive state (temperature, pressure, chemical potentials).
- has all of its parts at rest relative to one another.
- acts as an infinite system.
- is a sink and source for heat and materials
- has no chemical reactions occurring between its components.
- has an exergy value of zero.

Since exergy is evaluated with respect to a reference environment, its intensive properties partly determine the exergy of a flow or system. As the exergy of the reference environment is zero, the exergy is zero for a flow or system in equilibrium with it, i.e., when $T = T_o$, $P = P_o$ and $\mu_k = \mu_{ko}$ for all k.

Other characteristics of reference-environment models have been reported (Wepfer and Gaggioli, 1980; Sussman, 1981; Ahrendts, 1980; Dincer and Rosen, 2007).

The reference environment as an element of exergy analysis, and its role in relating exergy to environmental and ecological assessments, are discussed in depth in this chapter.

6.2. COMPARISON OF NATURAL AND REFERENCE ENVIRONMENTS

The natural environment does not possess the theoretical characteristics of a reference environment for a variety of reasons:

- The natural environment is not in equilibrium.
- The intensive properties of the natural environment vary spatially (e.g., from a desert to a rainforest) and temporally (e.g., from summer to winter).
- Many chemical reactions in the natural environment are blocked because the transport mechanisms necessary to reach equilibrium are too slow at ambient conditions.

As a consequence, models for the reference environment are normally used. Often these models seek a compromise between the theoretical requirements of the reference environment and the actual behavior of the natural environment.

6.3. MODELS FOR THE REFERENCE ENVIRONMENT

Several reference-environment models have been proposed, the most significant classes of which are described in the following subsections, based on discussions by Rosen and Dincer (1997a). For clarity, three important states related to the reference environment are defined:

- The dead state is the state of a system when it is in thermal, mechanical and chemical equilibrium with a conceptual reference environment (having intensive properties pressure P_o, temperature T_o, and chemical potential μ_{ko} for each of the reference substances in their respective dead states).
- The environmental state is the state of a system when it is in thermal and mechanical equilibrium with the reference environment, i.e., at pressure P_o and temperature T_o of the reference environment.
- The reference state is a state with respect to which values of exergy are evaluated. Several reference states are used, including environmental state, dead state, standard environmental state and standard dead state.

6.3.1. Process-Dependent Models

Process-dependent models contain only components that participate in the process considered in a stable equilibrium composition at the temperature and pressure of the natural environment. Bosnjakovic (1963) proposed such a model, which is not general but dependent on the process examined. This model is general and does not resemble the natural environment. Exergies evaluated for a specific process-dependent model are relevant only to the process, and cannot rationally be readily compared with exergies evaluated for other process-dependent models or used in environmental assessments.

6.3.2. Equilibrium and Constrained-Equilibrium Models

Equilibrium and constrained-equilibrium models consider a blending of some subsystems of the natural environment in an equilibrium or constrained-equilibrium condition.

Equilibrium Models

Ahrendts (1980) proposed a model in which all the materials present in the atmosphere, oceans and a layer of the crust of the Earth are pooled together and an equilibrium composition is calculated for a given temperature. The selection of the thickness of crust considered is subjective and is intended to include all materials accessible to technical processes. For all thicknesses considered (1-1000 m) and a temperature of 25°C, the model differs significantly from the natural environment. Exergy values obtained using these environments are significantly dependent on the thickness of crust considered, and represent the maximum work obtainable. Since there is no technical process available which can obtain this work, the equilibrium model does not necessarily yield meaningful exergy values when applied to real processes.

Constrained-Equilibrium Models

Ahrendts (1980) modified his equilibrium environment by excluding the possibility of forming nitric acid (HNO_3) and its compounds in calculating an equilibrium composition. That is, all chemical reactions in which these substances are formed are in constrained equilibrium, and all other reactions are in unconstrained equilibrium. For a crust thickness of 1 m and a temperature of 25°C, this model resembles the natural environment.

6.3.3. Reference-Substance Models

Natural Reference-Substance Models

With these models, a "reference substance" is selected for every chemical element and assigned zero exergy. Szargut (1967) proposed a model in which the reference substances are selected as the least valuable substances found in abundance in the natural environment. The criterion is consistent with the concept of simulating the natural environment, but is primarily economic and is vague for selecting reference substances. This model includes moist air, gypsum ($CaSO_4 \cdot 2H_2O$) and limestone ($CaCO_3$). The selection of reference substances in this manner simulates reasonably the natural environment.

Arbitrary Reference-Substance Models

In a related model which does not resemble the natural environment, reference substances are selected arbitrarily (Sussman, 1980, 1981). Exergy values evaluated with this model do not relate to the natural environment, and cannot be used rationally to evaluate efficiencies or environmental impact.

6.3.4. Natural-Environment-Subsystem Models

Such models simulate realistically subsystems of the natural environment. Although such reference environment models try to achieve a balance between the theoretical requirements of the reference environment and the actual behavior of the natural environment, they aim to mimic the characteristics of the natural environment as much as possible.

Basic Natural-Environment-Subsystem Models

One such model consists of saturated moist air and liquid water in phase equilibrium (Baehr and Schmidt, 1963). This model is a reasonable approximation of the natural environment surrounding a process and is especially useful if the constituents involved in a process are those in the reference environment or producible from the constituents of the reference environment. Where additional constituents are involved, or where more environmental or ecological detail is sought, a more complex model of the reference environment is often needed.

Such a natural-environment type of reference environment is illustrated in Figure 6.1, where the three main parts of the natural environment are highlighted.

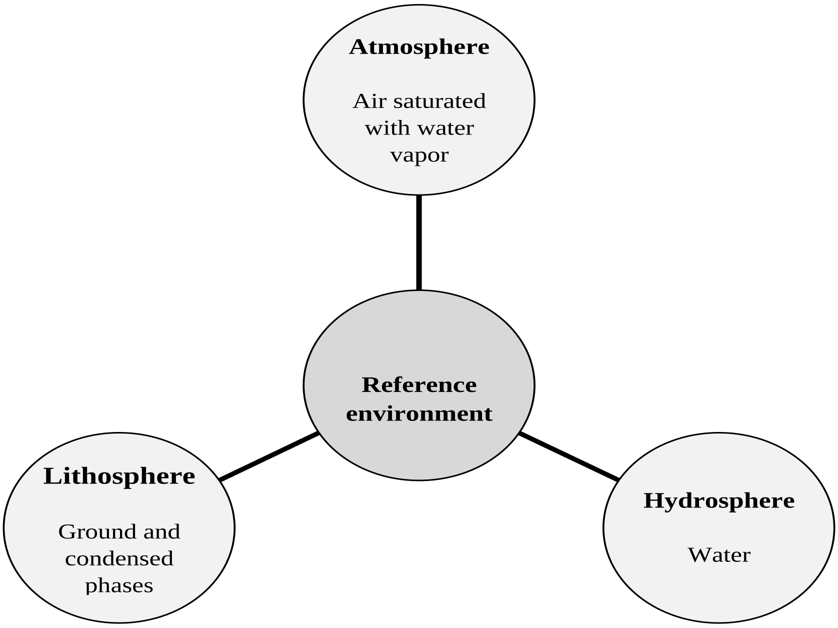

Figure 6.1. Conceptual representation of a reference-environment model for exergy analysis which simulates the characteristics of the natural environment.

Table 6.1. A reference-environment model based on the natural environment

Temperature, T_o	25°C		
Pressure, P_o	1 atm		
Composition	Gaseous	Atmospheric air saturated with H_2O at T_o and P_o, with the following constituent make up:	
		Constituent	*Molar percentage*
		Argon (Ar)	0.91
		Carbon dioxide (CO_2)	0.03
		Hydrogen (H_2)	0.01
		Nitrogen (N_2)	75.67
		Oxygen (O_2)	20.35
		Water (H_2O)	3.03
	Solid and liquid	Condensed phases at T_o and P_o:	
		Water (H_2O)	
		Limestone ($CaCO_3$)	
		Gypsum ($CaSO_4 \cdot 2H_2O$)	

Enhanced Natural-Environment-Subsystem Models

An extension of the basic model (Table 6.1) allows sulfur-containing materials to be analyzed and has a temperature T_o = 25°C, pressure P_o = 1 atm, and composition consisting of air saturated with water vapor and the following condensed phases at T_o and P_o: water, gypsum and limestone (Gaggioli and Petit, 1977; Rodriguez, 1980).

6.4. Reference-Environment Models for Environmental and Ecological Assessments

The reference environment may be modeled so as to achieve convenience in thermodynamic assessments, and such models may or may not simulate the natural environment. All reference environment models for exergy analyses can be used to assess thermodynamic losses. A reference environment that simulates the natural environment is needed to evaluate exergy efficiencies.

A reference environment that simulates the natural environment is also needed to evaluate the potential for environmental or ecological impact using exergy methods. The potential impact of emissions may be assessed when their exergies are evaluated relative to a realistic reference environment model.

The natural-environment-subsystem models for the reference environment provide a similarity between the reference and natural environments. These models extend the reference environment to the natural environment and permit exergy analysis to be introduced into environmental and ecological management. Some constrained-equilibrium and reference-substance models do so in part. Other reference environments described in this chapter do not necessarily mimic the natural environment.

6.5. Sensitivity of Exergy Quantities to Variations in the Reference Environment

It is important to understand quantitatively the sensitivity of exergy quantities to variations in the properties of and models for the reference environment. Such information is needed to determine the significance of the results of exergy analyses and exergy-based environmental and ecological assessments to the choice of

- a reference-environment model, and
- reference-environment properties.

Most energy and exergy values are dependent on the intensive properties of the reference environment. But the reference environment is not fixed, as it is often selected to simulate the accessible natural environment, e.g., often the reference environment pressure P_o is taken to be near 100 kPa and the reference environment temperature T_o is chosen such that 0°C ≤ T_o ≤ 50°C, while the chemical composition is taken to be similar to that of the accessible region of the crust of the Earth. Consequently the results of energy and exergy analyses, as well as environmental and ecological assessments based on exergy, generally are sensitive to variations in these properties. It is useful to have a quantitative understanding of the significance of these sensitivities, particularly for reasonable variations in reference environment properties. Otherwise, analysts often assume that small and reasonable changes in reference environment properties have little effect.

The need to understand the impact of variations in the intensive properties of the reference environment on exergy analyses and exergy-based environmental and ecological assessments is particularly important given the effects of climate change, which can alter the intensive properties of the natural environment, as explained in Section 6.5.4.

Very few discussions of these sensitivities have been reported to guide users. For instance, Wepfer and Gaggioli (1980) point out that exergy analyses of chemical plants are often relatively insensitive to variations in T_o and P_o, while the present author has reported for aerospace applications the impact on exergy analysis results of variations in reference environment properties at increasing altitudes in the atmosphere (see Section 18.2). In extreme cases, such as a rocket taking off from ground level and flying to space, the reference environment changes are large. The present author examined the sensitivities of energy and exergy values, as well as system analyses, to reasonable variations in reference environment properties (Rosen, 1986; Rosen and Scott, 1987; Rosen and Dincer, 2004b), and that work forms the basis of much of this section.

Here we describe the sensitivities to reasonable variations in reference environment properties of several energy and exergy values. Applications of this material are presented subsequently for aerospace operations (Section 18.2) and coal fired electricity generation (Section 20.3). In most applications, the main results of energy and exergy analyses, and environmental and ecological assessments based on exergy, are not significantly sensitive to reasonable variations in reference environment properties, but sometimes this is not so (as seen in the assessment in Section 18.2).

We define the sensitivity σ of a general quantity Y to a variation ΔX in a quantity X as

$$\sigma = \frac{Y(X+\Delta X)-Y(X)}{Y(X)} \tag{6.1}$$

where σ is a non-dimensional measure of the fractional change in Y due to a perturbation ΔX in X. Here, Y represents energy or exergy, and X a reference environment property.

6.5.1. Sensitivities of Non-Material Energy and Exergy Flows to Variations in Reference Environment Properties

Energy and Exergy of Work and Electricity

The energy and exergy values associated with shaft work and the work done by a system due to volume change are both independent of reference environment properties. Similarly, the exergy of electricity is independent of reference environment properties.

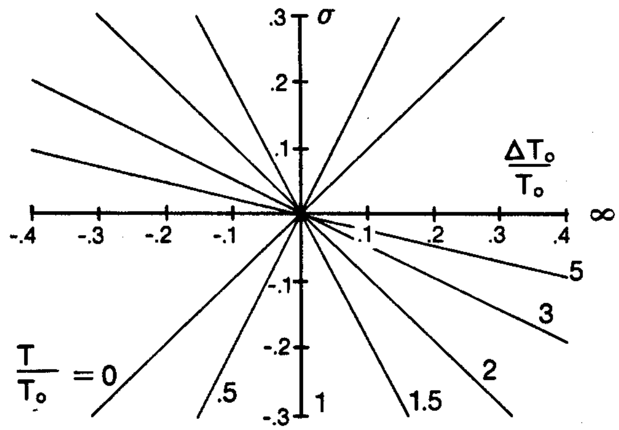

Figure 6.2. Variation with T_o of sensitivity σ of both thermal exergy Ex_Q and specific physical energy $h - h_o$ of an ideal gas, for a range of T/T_o values.

Thermal Energy and Thermal Exergy

Values of thermal energy Q are independent of the reference environment, while values of thermal exergy, $Ex_Q = (1 - T_o / T)Q$, are dependent only on T_o. The sensitivity of Ex_Q to a variation in T_o is given by Equation (6.1) with $Y = Ex_Q$ and $X = T_o$:

$$\sigma = \frac{Q\left[1 - \frac{T_o + \Delta T_o}{T}\right] - Q\left[1 - \frac{T_o}{T}\right]}{Q\left[1 - \frac{T_o}{T}\right]} = \frac{\Delta T_o}{T_o - T} \tag{6.2}$$

The sensitivity σ for Ex_Q is plotted against $\Delta T_o/T_o$ in Figure 6.2 for a range of T/T_o values. σ is small when Ex_Q is large (i.e., $T << T_o$ or $T >> T_o$), and large when Ex_Q is small (i.e., T is near T_o). The large sensitivity when $T \cong T_o$ is normally not significant because of the small magnitude of Ex_Q at that condition.

6.5.2. Sensitivities of Material Energy and Exergy to Variations in Reference Environment Properties

The physical energy and exergy associated with flowing streams of matter are generally dependent on T_o and P_o. The sensitivities are examined here for two common flows: an ideal gas and water. Then chemical exergy is examined.

Physical Energy and Exergy of an Ideal Gas

For an ideal gas,

$$h - h_o = c_p(T - T_o) \tag{6.3}$$

and

$$s - s_o = c_p \ln(T/T_o) - R\ln(P/P_o) \tag{6.4}$$

where specific heats are taken to be constant. Thus,

$$ex_{ph} = h - h_o - T_o(s - s_o) = c_p[T - T_o - T_o\ln(T/T_o)] - R\ln(P/P_o) \tag{6.5}$$

The term $h - h_o$ can be thought of as the specific physical energy associated with a flowing stream of matter. For an ideal gas, $h - h_o$ is dependent only on T_o, and the sensitivity of $h - h_o$ to a variation in T_o is given by Equation (6.1) with $Y = h - h_o$ and $X = T_o$:

$$\sigma = \frac{c_p(T - T_o - \Delta T_o) - c_p(T - T_o)}{c_p(T - T_o)} = \frac{\Delta T_o}{T_o - T} \tag{6.6}$$

This sensitivity to variations in T_o is the same as for Ex_Q (see Equation (6.2) and Figure 6.2).

The sensitivity of ex_{ph}, for $P = P_o$, to a variation in T_o is given by Equation (6.1) with $Y = ex_{ph}$ and $X = T_o$:

$$\sigma = \frac{c_p[T - T_o - \Delta T_o - (T_o + \Delta T_o)\ln(T/(T_o + \Delta T_o))] - c_p[T - T_o - T_o\ln(T/T_o)]}{c_p[T - T_o - T_o\ln(T/T_o)]}$$
$$= \frac{T_o\ln(1 + \Delta T_o/T_o) - \Delta T_o(1 + \ln(T/T_o + \Delta T_o)))}{T - T_o - T_o\ln(T/T_o)} = \frac{\ln(1 + \Delta T_o') - \Delta T_o'[1 + \ln(T'/(1 + \Delta T_o'))]}{T' - 1 - \ln T'} \tag{6.7}$$

where $\Delta T_o' \equiv \Delta T_o/T_o$ and $T' \equiv T/T_o$. The sensitivity of ex_{ph}, for $T = T_o$, to a variation in P_o is given by Equation (6.1) with $Y = ex_{ph}$ and $X = P_o$:

$$\sigma = \frac{-R\ln P/(P_o + \Delta P_o) + R\ln(P/P_o)}{-R\ln(P/P_o)} = \frac{\ln(1 + \Delta P_o/P_o)}{\ln(P_o/P)} \tag{6.8}$$

The sensitivity of ex_{ph} to variations in T_o and P_o can be observed using Equations (6.7) and (6.8) to be small when ex_{ph} is large and large when ex_{ph} is small.

Physical Energy and Exergy of Water

The values of $h - h_o$ and ex_{ph} for liquid water and vapor water depend on both T_o and P_o. For reasonable variations in T_o and P_o, values of ex_{ph} and $h - h_o$ respectively are listed in Tables 6.2 and 6.3 for liquid water at several states, and in Tables 6.4 and 6.5 for water vapor at several states. The base values for T_o and P_o are 298.15 K and 101 kPa respectively, and variations considered are $\pm 20^oC$ for T_o, and ± 10 kPa for P_o. Water in the liquid phase is taken to be the stable form in the environment. The sensitivities are small except when the magnitudes of $h - h_o$ and ex_{ph} are small (i.e., the stream is near T_o and P_o).

Table 6.2. Specific physical exergy ex_{ph} (in kJ/kg) for liquid water at several states as reference environment properties vary from base values (T_o = 25°C, P_o = 0.101 MPa)

State		P_o			T_o		
T (°C)	P (MPa)	T_o – 20°C	T_o	T_o + 20°C	P_o – 0.01 MPa	P_o	P_o + 0.01 MPa
5	0.101	0.0	2.94	11.50	2.96	2.94	2.93
25	0.101	2.87	0.0	2.74	0.013	0.0	–0.013
1000	100	1667	1569	1478	1569.26	1569.24	1569.23

Table 6.3. Specific base enthalpy $h - h_o$ (in kJ/kg) for liquid water at several states as reference environment properties vary from base values (T_o = 25°C, P_o = 0.101 MPa)

State		P_o			T_o		
T (°C)	P (MPa)	T_o – 20°C	T_o	T_o + 20°C	P_o – 0.01 MPa	P_o	P_o + 0.01 MPa
5	0.101	0.0	–83.7	–167.3	–83.73	–83.74	–83.75
25	0.101	83.7	0.0	–83.2	0.009	0.0	0.009
1000	100	3060	2977	2893	2976.69	2976.68	2976.67

Table 6.4. Specific physical exergy ex_{ph} (in kJ/kg) for water vapor at several states as reference environment properties vary from base values (T_o = 25°C, P_o = 0.101 MPa)

State		P_o			T_o		
T (°C)	P (MPa)	T_o – 20°C	T_o	T_o + 20°C	P_o – 0.01 MPa	P_o	P_o + 0.01 MPa
25	0.0032	166.5	–0.19	–161.3	–0.180	–0.193	–0.206
99.9	0.101	629.6	487.0	349.9	486.98	486.96	486.95
300	8	1175	1064	958	1063.74	1063.73.	1063.71
500	5	1493	1358	1228	1357.92.	1357.90	1357.89
600	10	1703	1569	1442	1569.49	1569.48	1569.46

Table 6.5. Specific base enthalpy $h - h_o$ (in kJ/kg) for water vapor at several states as reference environment properties vary from base values (T_o = 25°C, P_o = 0.101 MPa)

State		P_o			T_o		
T (°C)	P (MPa)	T_o – 20°C	T_o	T_o + 20°C	P_o – 0.01 MPa	P_o	P_o + 0.01 MPa
25	0.0032	2526	2442	2358	2442.02	2442.01	2442.00
99.9	0.101	2654	2571	2487	2570.56	2570.55	2570.54
300	8	2765	2681	2598	2681.46	2681.45	2681.44
500	5	3412	3328	3245	3328.24	3328.23	3328.23
600	10	3601	3517	3434	3517.24	3517.23	3517.22

Table 6.6. Specific chemical exergies (in kJ/g mol) proposed by various researchers for selected species, for T_o = 298.15 K and P_o = 0.101 MPa*

State	Species	Gaggioli and Petit	Baehr and Schmidt	Szargut	Wadsley	Ahrendts	Sussman
Liquid	Water, H_2O	0.0	0.0	3.17	1.72	0.05	0.0
	Methanol, CH_3OH	717	717	723	720	711	702
Gas	Oxygen, O_2	3.95	3.95	3.97	3.91	3.95	0.0
	Nitrogen, N_2	0.69	0.69	0.72	0.65	0.64	0.0
	Carbon dioxide, CO_2	20.1	20.1	20.2	19.9	14.2	0.0
	Water H_2O	8.67	8.60	11.76	10.31	8.64	8.59
	Sulfur dioxide, SO_2	288	–	304	302	241	0.0
	Carbon, C	411	411	411	410	405	394
	Hydrogen, H_2	235	235	238	237	235	237
	Hydrogen sulfide, H_2S	795	–	805	802	800	–
	Methane, CH_4	830	830	837	834	824	818
	Heptane, C_7H_{16}	4759	4757	4783	4776	4716	4667
	Ammonia, NH_3	337	336	340	339	337	339

* Compiled from data in Wadsley (1984).

Chemical Exergy and Base Enthalpy

The sensitivities of values of chemical exergy and base enthalpy to variations in reference environment properties are difficult to determine in general, given the chemical composition of the reference environment can vary greatly. Nonetheless, some insights are provided here regarding these sensitivities.

For several chemical species, specific chemical exergies are listed in Table 6.6, as determined by several researchers relative to the range of chemical reference environments they propose. For reference environments which approximately simulate the "accessible" natural environment (those of Gaggioli and Petit, Baehr and Schmidt, Szargut, and Wadsley), chemical exergies normally vary by less than 10% for any species. For reference environments which do not simulate the environment (those of Ahrendts and Sussman), chemical exergies can vary significantly.

When simulating different natural environments, chemical exergies for most substances normally do not vary greatly. For a gaseous mixture of N_2, O_2, CO_2, CO, H_2O and SO_2, for example, the chemical exergy evaluated by Wepfer (1979) relative to a reference environment having T_o = 298.15, P_o = 101 kPa and a composition typical of a desert region was shown to be 6.7% higher than that evaluated for a reference environment having the same temperature and pressure and a composition typical of a moderate-climate region. The effects of such a difference on plant performance are usually not too significant, although this is not always so.

Enthalpies evaluated relative to the stable components of the reference environment are referred to here as "base enthalpies." Base enthalpies are often used to allow comparisons of the results of energy and exergy analyses. Since values of base enthalpy are similar to values of chemical exergy for many species, base enthalpies like chemical exergies, are often not strongly sensitive to reasonable variations in the reference chemical environment.

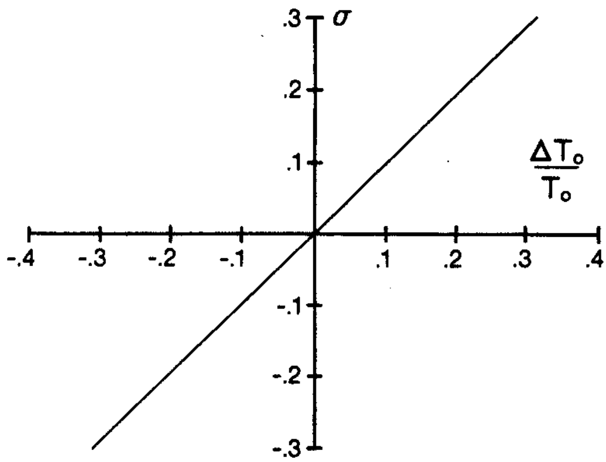

Figure 6.3. Variation with T_o of sensitivity σ of exergy consumption I.

6.5.3. Sensitivities of Exergy Consumption to Variations in Reference Environment Properties

The only reference environment property on which exergy consumption I (= $T_o\Pi$) is dependent is T_o. The sensitivity of I to a variation in T_o is given by Equation (6.1) with $Y = I$ and $X = T_o$:

$$\sigma = \frac{(T_o + \Delta T_o)\Pi - T_o\Pi}{T_o\Pi} = \frac{\Delta T_o}{T_o} \tag{6.9}$$

The sensitivity σ for I is plotted against $\Delta T_o/T_o$ in Figure 6.3. A variation in T_o causes a proportional variation in I. For the narrow range of T_o values normally used, the sensitivity of I to variations in T_o is relatively insignificant.

6.5.4. Relation to Climate Change

The need to understand the impact of variations in the intensive properties of the reference environment on exergy analyses and exergy-based environmental and ecological assessments is particularly important given the effects of climate change. Greenhouse gas emissions, which are considered by many to be the primary cause of climate change, have almost certainly led to a change in the composition of the atmosphere, which is a key component of the natural environment. For instance, the increase in atmospheric carbon dioxide concentrations since the onset of the industrial revolution has paralleled very closely the increase in anthropogenic fossil fuel over that period. The impact on the natural environment of climate change has at least two aspects, both of which affect exergy analyses and exergy-based environmental and ecological assessments:

- A change in the chemical composition of the natural environment. For instance, the mean global atmospheric carbon dioxide concentration is presently about 390 ppm on a volume basis. This is in contrast to values slightly over 300 ppm 50 years ago and 280 ppm in 1800. Predictions of the mean global atmospheric carbon dioxide concentration in the future range markedly, depending on the accuracy of predictive models and on measures societies adopt to mitigate climate change by reducing the concentration, but some predictions suggest values as high as 600-800 ppm. This change in an intensive property of the natural environment affects chemical exergy.
- A change in the temperature of the reference environment. The change in mean global atmospheric carbon dioxide concentration is considered by many to lead to an increase in the mean global temperature (i.e., global warming), due to how carbon dioxide and other greenhouse gases allow shortwave radiation from the sun to pass through the atmosphere of the Earth, but block some of the radiation released by the Earth from leaving the atmosphere (i.e., the greenhouse effect). Predictions of mean global temperature increases of range from 2ºC to 6-8ºC. This change in an intensive property of the natural environment affects physical exergy values.

6.6. CLOSING REMARKS

The reference environment is a hypothetical system that is selected and therefore may or may not simulate the natural environment. However, exergy analyses can extend beyond thermodynamic losses to the potential for environmental and ecological impact when a suitable reference environment is selected that mimics the natural environment. Extending the reference environment to the natural environment is therefore an important aspect of extending exergy to exergy-based environmental and ecological management. An understanding is also needed of the sensitivity of exergy quantities to variations in reference environment, given that exergy-based assessments, whether technical or environmental or ecological, are dependent on the properties of the reference environment.

Chapter 7

EXERGY AND THE ENVIRONMENT

OVERVIEW

The potential of exergy to be an indicator, or part of a broader indicator, for environmental impact is discussed. Various relations are identified between exergy and the environment that support this idea, while acknowledging that exergy itself theoretically is not a direct measure of environmental impact. It is nonetheless demonstrated that an exergy-based indicator for the environmental impact of waste emissions may be able to provide an enhanced understanding of, and more rational approaches to mitigating, the environmental impact associated with such emissions, and that exergy also can be used in the attribution of emissions for complex processes.

The relations between exergy and the environment reveal some underlying fundamental patterns and forces affecting environmental changes, and can help researchers better address environmental damage. Of course, increasing efficiency can reduce environmental impact by reducing exergy losses. But the second law and environmental impact can also be linked through exergy because, among other reasons, exergy is a measure of the departure between the states of a system and the environment.

The potential of exergy as an indicator for the environmental impact is discussed in this section. To support the arguments, relations between exergy and the environment are described, and exergy is compared with other indicators for the environmental impact of waste emissions. It is demonstrated that an exergy-based indicator for the environmental impact of waste emissions may be able to provide a better understanding of the environmental impact associated with emissions and rational mitigation approaches.

7.1. TRENDS AND GENERALITIES

On a simple level, increasing efficiency can reduce environmental impact by reducing exergy losses (including emissions). Increased efficiency also reduces the requirement for energy production, transportation, transformation and distribution systems, all of which impact the environment.

On a more complex level, a potentially useful way to link the second law and environmental impact is through exergy because it is a measure of the departure of the state of a system from that of the environment (Ayres et al., 1998; Berthiaume et al., 2001; Creyts and Carey, 1997; Gunnewiek and Rosen, 1998; Frangopoulos and von Spakovsky, 1993; Rosen and Dincer, 1997a, 1999; Dincer and Rosen, 2007; Sciubba, 1999; Wall and Gong, 2001a, 2001b; Baumgärtner and de Swaan Arons, 2003; Jorgensen and Svirezhev, 2004). 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.

Thus, exergy can be applied beyond thermodynamics to understanding waste emissions and reducing their environmental impact. For clarity, a waste emission is defined here as a release to the environment of a material not considered usable. Furthermore, exergy is a measure of potential of a substance to cause change. The exergy of an emission to the environment, therefore, is measure of the potential of the emission to change or impact the environment. The greater the exergy of an emission, the greater is its departure from equilibrium with the environment, and the greater may be its potential to change or impact the environment. The exergy of an emission is zero only when it is in equilibrium with the environment and thus benign. These points suggest that exergy may be, or provide the basis for, an effective indicator of the potential of an emission to impact the environment.

As discussed subsequently (Chapter 13), applications of exergy are increasing in studies of environmental impact (Ayres et al., 1998; Berthiaume et al., 2001; Creyts and Carey, 1997; Gunnewiek and Rosen, 1998; Frangopoulos and von Spakovsky, 1993; Rosen and Dincer, 1997a, 1999; Dincer and Rosen, 2007; Sciubba, 1999; Wall and Gong, 2001a, 2001b; Baumgärtner and de Swaan Arons, 2003; Jorgensen and Svirezhev, 2004), with the aim of improving understanding of environmental impact and developing better predictors and indicators of environmental impact, especially for environmental emissions.

Others recognize the potential of exergy to provide a measure of environmental impact. For instance, Tribus suggests that exergy analyses of the natural processes occurring on Earth could form a foundation for ecologically sound planning because it would indicate the disturbance caused by large-scale changes (Tribus and McIrvine, 1971). Szargut (1978) recognizes that all wastes released into the environment, from industrial processes or other sources, possess some exergy, and thus can disturb the equilibrium of the environment. The greater the exergy of the waste stream, the greater is the disturbance of the environment. Szargut uses this exergy as a component in determining a coefficient of ecological cost for any product. Also, the Consortium on Green Design and Manufacturing at the University of California-Berkeley (http://cgdm.berkeley.edu) carried out a project entitled “Exergy as an Environmental Indicator” to increase the practical application of exergy analysis for rectifying the problems associated with material and energy flows in industry. That work focused on developing a generalizable technique to calculate exergy in an industrial setting, exploring the significance of environmental ground states and establishing the requisite databases for a diverse range of analyses (Connelly and Koshland, 1997, 2001a, 2001b).

A recent study (Dincer and Rosen, 2007) of thermodynamics and sustainable development suggests exergy is an important tool for obtaining sustainable development. That study showed

- exergy destruction should be appropriately reduced to make development more sustainable, and

- environmental effects associated with emissions and resource depletion may be expressible in terms of an indicator based on physical principles.

7.2. TYPES OF ENVIRONMENTAL IMPACT INDICATED BY EXERGY

Several exergy-environment relations are described that explain the types of environmental impact predictable using exergy.

7.2.1. Emission of Waste Exergy

The exergy associated with a process waste emission to the environment represents in some ways a potential for environmental damage. Typical process wastes have exergy, a potential to cause change, due to being out of equilibrium with the environment. When emitted, this exergy represents a potential to change the environment. Usually, emitted exergy causes a change which is harmful to the environment (e.g., deaths of fish in lakes as stack gases interact with the environment), although emitted exergy sometimes causes a change perceived as beneficial (e.g., increased fish growth near the cooling-water outlets from thermal power plants).

Emissions of exergy to the environment can also interfere with the net input of exergy via solar radiation to the Earth. The carbon dioxide emitted in stack gases from many processes changes the atmospheric CO_2 content, affecting the receiving and re-radiating of solar radiation by the Earth.

The relation between waste exergy emissions and environmental damage is recognized by several researchers. Reistad (1970) proposed an air-pollution rating in which the air-pollution cost for a fuel is estimated as either the cost to remove the pollutant or the cost to society of the pollution (i.e., an appropriate tax if pollutants are released), which he thought preferable to the mainly empirical ratings then used.

Not all types of waste emissions pose equal risks. A waste emission possesses exergy when in a state of mechanical or thermal or chemical disequilibrium with the reference environment. A material generally has two exergy components, which behave differently environmentally:

- Physical exergy. The exergy of an emission attributable to mechanical and thermal disequilibrium is not usually significant and its potential environmental impact is limited. That is, a pressure difference between an emission and the environment normally dissipates shortly after the emission enters the environment, and a temperature difference is normally localized near the emission source and can be controlled. For example, thermal pollution in a lake is often concentrated near cooling water discharges, causing local water temperatures at the pipe exit to be a few degrees higher than the average lake temperature and affecting somewhat nearby plant and animal life. Usually, physical exergy material emissions (i.e., emissions that are in chemical equilibrium with the local environment, but at a different temperature and/or pressure) are not strongly threatening environmentally. Contributions of heat to the temperature of the land, water and air are small compared to the effects of solar energy. Also, emissions at different pressures than the atmosphere quickly expand or contract on entering the environment, and in general have little or no impact on the biosphere. Of course, the pressure difference represents an opportunity for work, and can be utilized by a device such as a turbine.

- Chemical exergy. The exergy of an emission due to chemical disequilibrium (i.e., chemical exergy) is often significant and not localized, and can sometimes cause serious damage to the biosphere due to chemical effects. Furthermore, material emissions can be carried far from where they originate by prevailing winds and other weather effects. Consequently, chemical exergy appears to correlate somewhat with the potential for environmental impact.

7.2.2. Degradation of Resources and Order

The degradation of resources found in nature is a form of environmental damage.

A resource can be viewed as a natural or artificial material in disequilibrium with the environment. A resource has exergy. For resources like ores, composition is valued and purification processes exist to increase their value (and their exergy) by using at least an equivalent amount of exergy elsewhere (e.g., combusting fuel to produce heat for refining). For other resources (e.g., fuels), their reactivity is usually valued.

By avoiding exergy degradation through increased efficiency, environmental damage is reduced. Increased efficiency also reduces exergy emissions, which also can represent a potential to harm the environment.

More generally, the degradation of order, whether in a fossil fuel or a pure substance, is a type of environmental damage. Combustion reduces order as does the release of a pure substance like carbon dioxide into the atmosphere and its subsequent mixing and dilution.

As an open system, the Earth receives exergy from the sun, which is valued. The energy received from the sun is ultimately radiated out to the universe. Environmental damage can be reduced by exploiting the openness of the Earth, i.e., utilizing solar radiation, instead of degrading resources found in nature to supply exergy.

7.2.3. Creation of Chaos

The creation of chaos or disorder is a form of environmental damage. Entropy is a measure of chaos. A high-entropy system (e.g., carbon dioxide emitted to and mixed in the atmosphere) is more chaotic or disordered than one of low entropy (e.g., pure CO_2 in a tank).

The difference between the exergy values of a system in ordered and disordered states is a measure of the minimum work required to order the chaotic system, e.g., the minimum work required to extract emitted carbon dioxide from the atmosphere. In practice, more work is needed, as the minimum work applies to a reversible clean-up process. Alternatively, the exergy destroyed when effluents are released to the atmosphere can be viewed as a measure of the order destroyed.

7.2.4. Comparison

The types of environmental impacts described above have similarities and differences, which are discussed here.

The decrease in environmental impact in terms of the measures discussed in this section with increasing exergy efficiency is depicted qualitatively in Figure 7.1. Exergy methods also correlate with sustainability, also shown in Figure 7.1, in terms of the degree to which human activity can continue without difficulty in accessing resources or harming the environment. The limiting cases in Figure 7.1 are significant. As exergy efficiency nears 0%, sustainability approaches zero because exergy-containing resources are used but nothing is accomplished. Also, environmental impact becomes increasingly great because, to provide a fixed service, an ever-increasing quantity of resources must be used and a correspondingly increasing amount of exergy-containing wastes is emitted. As exergy efficiency approaches 100%, environmental impact approaches zero, since exergy is converted from one form to another without loss. Also sustainability becomes increasingly great because the process approaches reversibility, i.e., no losses occur so the process can go forwards and backwards indefinitely.

It may seem contradictory that exergy in the environment is valued in the form of resources and problematic in the form of emissions. Including the word "restricted" rationalizes these statements, as shown in Figure 7.2. Exergy restricted in a system represents a resource, while exergy emitted to the environment in an unrestricted way represents a kind of driving potential for environmental damage.

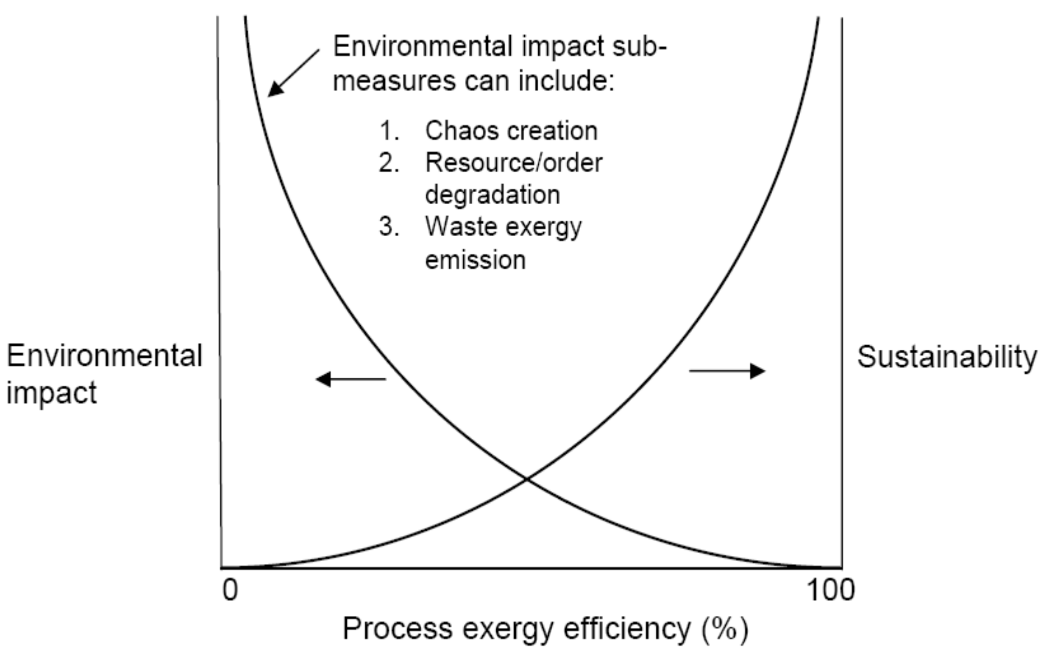

Figure 7.1. Qualitative depiction of the dependence of the sustainability and environmental impact of a process on its exergy efficiency. Several different exergy-based representations of environmental impact are shown.

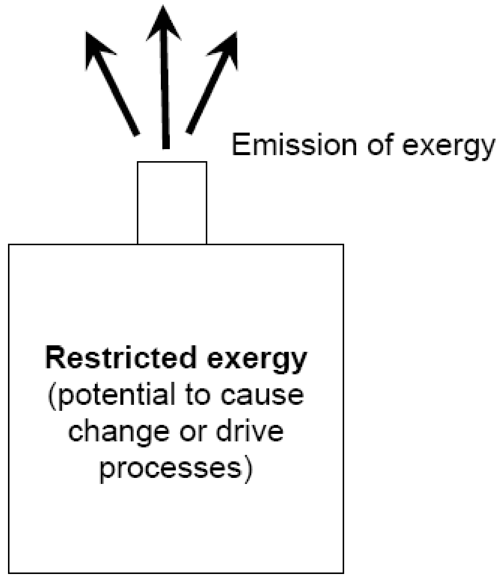

Figure 7.2. Comparison of restricted exergy, which is contained in a fixed space, and unrestricted exergy, which is free to disperse throughout the environment.

7.3. Exergy as an Indicator for Potential Environmental Impact of Emissions

Increasing attention has been devoted over the last few decades to better understanding the relations between energy use and the environment, largely because energy processes (e.g., production, transformation, transport and end-use) impact the environment. Environmental costs are usually associated with thermal, chemical, nuclear and other emissions. Increasing efficiency can reduce emissions, although increasing efficiency generally entails greater use of materials and energy resources, increasing the associated environmental burdens and somewhat offsetting the environmental gains of improved efficiency.

A major challenge in reducing the environmental impact of designs involves determining environmentally advantageous configurations and selecting the most appropriate from competing options. This selection is made difficult by the complex relationship between the technology considered and the characteristics of the effluents. Process or technology changes generally affect effluent characteristics, e.g., flow rate and composition. Evaluating alternatives, therefore, often requires comparisons of the relative environmental characteristics of different effluents. Existing methods for performing such analyses focus primarily on subjective ranking techniques, and often are based on energy.

Although data on the geographic distribution of energy utilization indicate a close correlation between a country’s energy consumption and economic development, a correlation between a country’s energy consumption and the degradation of its environment does not appear evident. That is, energy itself does not seem to provide a good indicator of the environmental impact of waste emissions.

Many researchers agree that exergy is an objective indicator capable of providing insights into potential environmental impact. Exergy analysis provides information about the quality of energy and material that is physically meaningful. Because of its origins within the thermodynamic community, however, to date few applications and investigations have been undertaken of the potential of exergy methods for better understanding of and reducing environmental impact, even though to appropriately reduce energy consumption and the related environmental impact, such knowledge is beneficial.

The exergy contents of waste emissions are more meaningful than the corresponding energy contents as measures of potential for environmental impact. By definition, material and energy flows only possess exergy when in disequilibrium with a reference environment. The exergy associated with waste emissions has the potential to cause environmental damage, particularly when it is released in an unrestricted manner into the environment. Some believe that by considering the exergy content of a waste emission, rational and meaningful assessments can be made of the environmental impact potential of the emission. The present author has carried out several studies on this topic (Berthiaume et al., 2001; Gunnewiek and Rosen, 1998; Rosen and Dincer, 1997a, 1999; Dincer and Rosen, 2007). This use of exergy is tied to its relation with the reference environment which, as noted earlier, is used in exergy analysis.

An exergy-based framework has been proposed by Simpson and Edwards (2011) for evaluating environmental impact, including two parts: environmental exergy analysis and anthropocentric sensitivity analysis. The framework provides a fundamental basis for valuing environmental interactions independent from their secondary impacts, e.g., global warming and photochemical smog. To extend exergy to analyze environmental interactions, the reference environment is modified with non-equilibrium thermodynamic principles. The results can be interpreted for decision making, but exhibit some subjectivity.

The environmental impact of processes and systems is related directly to the exergy input and destruction. One indicator of this environmental impact is the depletion factor D_p, which is the ratio of the exergy destruction I to the input exergy Ex_{in}:

$$D_p = I/Ex_{in} \tag{7.1}$$

The depletion factor represents the fraction of the input energy as fuel or in other forms that is dissipated rather than converted to useful products or services.

7.4. Exergy as an Indicator for Sustainability

The depletion factor has been extended to a measure of sustainability, the sustainability index SI. This index can be expressed as the inverse of the depletion factor:

$$SI = 1/D_p \tag{7.2}$$

The sustainability index indicates the effectiveness of a process in terms of the amount of exergy output per unit exergy destruction in a process or system. As a system or process becomes more sustainable system, its sustainability index increases, indicating reduced exergy destruction and, correspondingly, environmental impact.

Several researchers have examined the relation between the concepts of sustainability and thermodynamics. For instance, Wall (2010) describes how exergy and exergy-based methods offer potential to support sustainable development. Also, on the basis that resource consumption of any kind can be quantified solely in terms of exergy flows, Sciubba and Zullo (2011) demonstrate for sufficiently complex systems the existence of thresholds, below or above which the system exhibits an ability to remain in a self-preserving condition (which they take to be sustainable).

7.5. Emissions Allocations

Environmental emissions may be distributed among outputs and accumulations in a system in multiple ways. This observation is important and often the cause of confusion, particularly when there is more than one product. The allocation of emissions often depends on such factors as the type and purpose of a device and other considerations. If emissions are not allocated appropriately, it is difficult to gauge the environmental performance of a device and in some instances to attribute the causes of environmental damage.

Confusion arises most commonly for devices for which there are multiple products. In cogeneration systems which produce multiple products, for example, emissions can be allocated entirely to one of the products, or divided among the products. If this determination is not made properly, emissions may be attributed inappropriately and the environmental performance of a device or process may be incorrectly assessed.

Sometimes a pseudo-scientific approach to emissions allocation is taken and emissions are allocated proportionally to all outputs and accumulations of a quantity (such as mass or energy or exergy). Alternatively, emissions are sometimes allocated proportionally to non-waste outputs and accumulations of a quantity. Such approaches often do not allocate emissions in ways considered to be realistic and reasonable relative to market forces and industrial and societal perceptions.

7.6. Limitations and Critical Assessment

Apart from the fact that our understanding of the relations between exergy and the environment is in its infancy and still undergoing development, some researchers question whether exergy is adequately related to environmental impact and ecology to form a useful tool, or the degree to which such relations can form the basis of tools. Some examples follow.

Gaudreau et al. (2009) state that exergy methods have many notable benefits, but that the use of exergy as a measure of resource value or waste impact is tenuous. They feel that the limitations include an incompatibility between exergy *quality* and resource *quality*, an inability of exergy to characterize non work-producing resources via concentration exergy, and problems with the exergy reference environment.

Sciubba and Wall (2007) note that, although it is intuitive that exergy – due to its definition – can be regarded as some sort of thermodynamic indicator of the environmental impact of a process, exergy is not a rigorous measure of environmental impact. They note that equating exergy emissions to the environment with pollution is in part qualitatively correct, but not quantitatively valid, and suggest that the interconnection of exergy with environmental issues in a broad sense needs to be explored in more depth.

Hammond and Winnett (2009) critique the influence of thermodynamic ideas on ecological economics, and suggest that thermodynamic insights as typically employed in ecological economics are analogues or metaphors of reality, and that they need to be empirically tested against the real world.

These limitations and critiques are reasonable, and in most cases linked to the newness of disciplines linking exergy with environmental impact and ecology. Further research is needed to address these and other concerns with the approach as the discipline matures.

7.7. Closing Remarks

Although not a direct measure of environmental impact, exergy appears to have the potential be an indicator, or the basis for an indicator, of environmental impact. The relations identified between exergy and the environment support this supposition. It is demonstrated that an exergy-based indicator for the environmental impact of waste emissions may be able to provide an enhanced understanding of, and more rational approaches to mitigating, the environmental impact associated with waste emissions. It is further shown that exergy can be used in the attribution of emissions for complex processes. An exergy-based indicator may be usable directly, or within other measures of environmental impact and sustainability.

Chapter 8

Exergy and Ecology

Overview

Ecological aspects of exergy are described. Exergy is shown to be useful in modeling ecological systems and in understanding various ecological observations and phenomena, including ecosystem reactions, growth patterns, maturity, biodiversity and health. Exergy is also seen to be utilizable in ecosystem management, and related to concepts like emergy and eco-exergy. The relations and understanding provided through applying exergy to ecology and ecosystems have significant applications.

Exergy is useful in ecology and the management of ecological systems. For instance, Jorgensen and Svirezhev (2004) present a consistent and complete ecosystem theory based on thermodynamic concepts, applicable to ecological systems. In that work, the first and second laws of thermodynamics are interpreted in an ecosystem context, and Prigogine's far-from-equilibrium thermodynamics is used on ecosystems to explain their reactions to perturbations. The authors note that exergy provides a more profound and comprehensive explanation of the ecosystem's reactions and growth patterns, and utilize exergy to explain the trophic chain, the global energy and radiation balance, and the reactions of ecological networks.

Exergy is also seen to explain ecological observations, and to be useful in assessing ecosystem health and developing ecological models. In this chapter, many of the relations between exergy and ecology are described and assessed. These relations are important, as they form the foundation of exergy-based ecological methods.

An informative introduction to systems ecology has recently been published by Jorgensen (2012), which provides an excellent resource for those desiring more background or further reading. That book describes ecosystem theory based on thermodynamics (including exergy), hierarchy theory, and network theory. A background on exergy use in ecosystems analysis, along with challenges, has also been published recently (Pastres and Fath, 2011).

8.1. TRENDS AND GENERALITIES

The thermodynamics of open systems suggests that a goal function of ecosystems is to maximize their dissipation of exergy fluxes by maximizing internal exergy storage as biomass, biodiversity and complex trophical networks, and that human activity can decrease ecosystem exergy by decreasing biomass or internal complexity.

Human economic activity can turn the “natural capital” in highly-ordered self-producing ecosystems (e.g., coral reefs, marine estuaries, forests, grasslands, salt marshes) with their rich accumulations of resources (e.g., arable soils, aquifers, fossil fuel and mineral deposits) into damaged and disordered ecosystems (e.g., despoiled landscapes, eroded farmlands, depleted fisheries, anthropogenic greenhouse gases, acid rain, mine tailings) with degraded forms of energy and matter. Thermodynamics in general and exergy in particular are important in understanding ecosystems because the ordered ecosystems have high use potential (or high exergy or low entropy) and the disordered systems have little use potential (or low exergy or high entropy).

Nielsen (2000) considers a hierarchy of embedded systems for ecosystems to facilitate applications of thermodynamics. In that work, flows of an ecosystem in terms of exergy are assessed and the system is arranged as a hierarchically ordered sequence of systems, thermodynamically embedded in each other. Nielsen feels that this approach provides a framework that permits a unification of thermodynamic and network views of ecosystems, which facilitates environmental and other analyses on a common basis. Nielsen illustrates the approach for an aquatic food chain with recycling via bacterial action.

In some ways, many of these ideas are captured by Wall (1997, 2003), who suggests that living systems thrive on exergy.

8.2. EXERGY, LIFE AND EVOLUTION

Exergy and other concepts stemming from the second law of thermodynamics have been linked to the evolution of life.

8.2.1. The Second Law and Evolution

Schneider and Kay (1994) argue that life can be viewed as a manifestation of the second law. Also, Salthe (2005) applies to nature the concept of energy quality, determining the energy that must be dissipated to accomplish some work. Although developed from economic considerations, energy quality can be viewed as projecting from energy dissipations. Salthe notes that work done by an abiotic dissipative structure would lack positive economic significance, and so would be difficult to mark as a starting point for calculating energy quality, and that the destructive work from phenomena such as hurricanes or floods would have negative economic consequences and thus also not merit quality calculation. But abiotic work led to the origin of life, in that some kinds of abiotic dissipative structures had to have been the framework that fostered this process (Salthe, 2005). Since all dissipative structures exhibit thermodynamic and information organization, they may provide the context for the origin of something. By starting the forward calculation from the ultimate beginning, and considering a driving energy (e.g., insolation of some area or the thermal energy from inside the Earth), evolution can be contemplated. Nature has many energy gradients which could maintain evolutionary change as energy quality is continually dissipated.

8.2.2. Entropy and Evolution

The application of entropy in theories of evolution has been discussed in the past e.g., Collier (1986). A theory of general evolution is proposed to be possible by Swenson (1989) based on second law concepts and the principle of maximum entropy production.

Ideas relating evolution and entropy have also been used in efforts to develop a unified theory of biology (Brooks and Wiley, 1988).

8.2.3. Exergy and Evolution

Wall (1997, 2003) states that exergy destruction is the driving force for the evolution of systems all sizes, from cellular to cosmic. He adds that such exergy destruction should be reduced to as low a level as feasible to manage natural resources properly.

Evolution of life has been specifically proposed as linked to exergy. Jorgensen (2007a), for instance, determined the eco-exergy density and eco-exergy flow rate, as function of time, for evolution, and found that exergy density and exergy flow rate are excellent descriptors for evolution. Self-organizing systems such as organisms grow in complexity exponentially, and similar behavior is observed for exergy density. Jorgensen observes that the rate of increase in complexity is increasing, and that the first primitive life form could have been comprised of cells with less complexity than prokaryote cells.

8.3. Exergy-Based Ecological Indicators

8.3.1. General Entropy- and Exergy-Based Methods

Entropy has been argued to be a controlling factor for complex ecological processes (Mauersberger, 1995). Further, many exergy-based indicators have been proposed, some of which are described in this section.

Exergy and ecology have been demonstrated to be related (Jorgensen, 1992b), and exergy has been used widely as an objective function in many ecological models. Exergy and material flows in industrial and ecological systems have recently been examined (Ukidwe and Bakshi, 2011). An increasing number of articles address theoretical aspects of modeling and describe how models reveal ecosystem properties. About 20% of published models are for aquatic ecosystems. Recent trends in ecological models and their applications to aquatic ecosystems have been described, including their characteristics, advantages and disadvantages (Jorgensen, 2002a). Model calibration for aquatic and other ecosystems is also presented in that work, as are possible hybrids of the presented model types.

Ecosystems have been hypothesized to develop according to increases in four system attributes: ascendency, storage of exergy, ability to dissipate external gradients in exergy, and network aggradation. Ulanowicz et al. (2006) reconcile the attributes of ecosystems by considering exergy, information and aggradation. The four attributes are seen to have a theoretical consistency, and a core single factor responsible for all four separate descriptions is proposed. Marques et al. (1998) propose exergy as a holistic ecosystem indicator.

The evaluation of exergy for organisms has received significant attention. For instance, the applicability of genome size in exergy calculations has been investigated (Debeljak, 2002). Also, the utilization of nuclear DNA in determining the exergy of organisms in biomass has been examined (Fonseca et al., 2000). In that research, the application of ecological exergy as a system-oriented development indicator of ecosystems is examined. The applicability of DNA contents of several groups of organisms, assessed by flow cytometry or obtained from literature, to be weighting factors to estimate ecological exergy of biomass and organisms, as proposed by Marques et al. (1997), is discussed. Theoretical and practical aspects of the approach are discussed, considering reliability and applicability in exergy-based ecological studies.

8.3.2. Exergy, Buffering Capacity and Constraints

The buffering capacity of ecological systems has been investigated, e.g., the relation of exergy to the buffering capacity of ecosystems was investigated by Jorgensen (1982).

Exergy has also been argued to be related to ecological constraints (Jorgensen, 1992a).

8.3.3. Exergy and Structural Changes

Different ecosystem structures may prevail under different environmental circumstances. Ecological models have been used to show that structural changes are accompanied by increased exergy (Jorgensen, 1988). The need for models with dynamic structure has been discussed by Bendoricchio and Jorgensen (1997), who provide the theoretical rationale for applying exergy as goal function and who contrast traditional models with those having dynamic structure. The application of exergy in structural-dynamic modeling has also been illustrated by other researchers, e.g., Nielsen (1990).

Further, Jorgensen et al. (2002) argue that an exergy index can be used with ecosystem models to determine which structures will prevail under a given set of environmental circumstances, with the structure having the highest exergy prevailing. The method can also successfully predict structural changes. Jorgensen et al. (2002) tested the method successfully for the Mondego Estuary in Portugal and feel the method has general applicability.

Many feel that exergy is an effective measure of the information level of communities. The exergy can be difficult to evaluate and trends in community dynamics are often difficult to ascertain since communities consist of different species which vary in complex manners. Consequently, Park et al. (2001) implemented artificial neural networks in patterning and predicting exergy by utilizing the capabilities of such networks for information extraction and self-organization. They used data on benthic macroinvertebrate communities from streams, and patterned the time development of exergy at the sample sites through training by the

Kohonen network. The trained mapping was able to characterize the development trend of exergy for differing sample sites in differing time periods. Exergy relations were also determined by back-propagation, allowing the prediction of exergy at other sampling times.

8.3.4. Exergy Efficiencies of Ecological Processes

Exergy efficiencies for ecological processes can be determined in numerous ways. Ecologically based exergy analysis, combining exergy analysis and the characteristics of living systems, was suggested more than two decades ago as a method for ecological energy research. Zhou et al. (1996) propose evaluation methods for different types of exergy in living systems, considering the relevant physical-chemical and physiological-ecological processes. Exergy balances for animal and plant life can be constructed with this method, accounting for energy quantity and quality. Four ecological exergy efficiency indices for evaluating different ecological processes are proposed based on these balances.

Exergy analysis has been extended for life cycle assessment and sustainability evaluation of industrial products and processes, but such extensions usually do not account for the important role of ecosystems in sustaining industrial activity (Hau and Bakshi, 2004).

8.3.5. Exergy and Maturity

Exergy has been suggested as a measure of ecosystem maturity. This observation comes from a ranking of many steady-state models of aquatic ecosystems on the basis of maturity, quantified using several of Odum's attributes of ecosystem maturity (Christensen, 1995). A comparison of that ranking to rankings based on various ecosystem goal functions shows that maturity exhibits a strong negative correlation with relative ascendency, and thus a strong positive correlation with system overhead, a possible measure of ecosystem stability. The analyses suggest that exergy may be an appropriate goal function, and that comparisons of ecosystem models may be useful for enhancing understanding of ecosystem characteristics, notably sustainability.

8.3.6. Exergy and Extremal Principles and Optimization

Ecological indices are used to provide summary information about a particular aspect of ecosystem behavior. The hypothesis is often made that ecosystems are optimizing exergy. That is, exergy is thought to act as a quality indicator and to direct and govern the development of parameters in the ecosystem. The effect of applying exergy as an optimizing function in modeling has been tested in a structural dynamical model. For instance, such a model was tested, which describes the development due to biomanipulation of the phytoplankton community in a shallow lake (Nielsen, 1995). In that test, exergy is considered the free biogeochemical energy of a system compared to its surroundings, and is proposed as a goal function for ecosystem development. Unconstrained optimization leads to unrealistic results, but introducing constraints on parameters can improve results. Examples of constraints include changing optimization intervals to mimic the response time of the system, illustrating its memory or resilience, and modifying the possible change per interval reflecting the variation capability of system genetic pools (Nielsen, 1995). Introducing such constraints affects the rate with which the model evolves with time, in that decreasing intervals and increasing rate speeds up the system. Parameters are usually manipulated in accordance with observed dominance in natural ecosystems. In the study of Nielsen (1995), the parameter most often changed was the maximum growth rate of the algae.

The observed shift in composition in a macrophyte society is a general problem that can be understood using exergy. For instance, the optimization of different exergy forms in macrophyte societies has been investigated (Nielsen, 1997) by simulating the structural dynamics of the macrophyte societies in Denmark (considering the estuary Roskilde Fjord), Italy (considering the Lagoons of Venice) and Portugal (considering the estuary at Figueira da Foz). It is seen to be possible to simulate the competition between the species and allow spatial coexistence through time with a simple model based on only growth capacity, light and temperature characteristics. Four types of exergy (traditional exergy, internal exergy, structural or modern exergy, normalized exergy) proposed as goal functions in ecosystem development are examined and used in optimization activities. The behavior of the various exergy forms differ considerably temporally, yet except for normalized exergy they are observed to behave similarly as goal functions.

A dynamic structural model able to describe the changes in phytoplankton biomass and diversity was developed and tested to determine if it behaves according to the hypothesis that ecosystem reactions strive to maximize exergy under prevailing conditions (Jorgensen and Padisak, 1996). The work used data from Keszthely Bay, Lake Balaton. The results aid efforts to use the exergy maximization principle as a general guide to explain ecosystem reactions.

Extremal principles or ecological orientors or goal functions are commonly used today in theoretical ecology, and many such principles have been proposed. Exergy and ascendency are two widely accepted goal functions. Ray (2006) optimizes these goal functions in an aquatic ecosystem model of planktonic and fish systems. Varied sizes are considered of phytoplankton and zooplankton, with parameter values varied with body size following the allometric principle. The two goal functions predict different but realistic results for self-organization of the model system.

Fath and Cabezas (2004) contrast two ecological indices and their potential use as ecological goal functions: exergy and Fisher Information. The latter is an old statistical measure that has recently been used to detect change in a system regime and as a measure of system order. The measure considered for exergy includes a weighting factor for the complexity of the ecological species. The indices are compared on a ten-compartment food web model undergoing five perturbation scenarios. Although simple, the food web model demonstrates that exergy and Fisher Information usually respond differently, e.g., one increases due to a perturbation while the other decreases and vice versa.

8.3.7. Exergy and Dissipation

Dissipation stems from the second law of thermodynamics, and is manifested as exergy destruction or entropy creation. Dissipation of energy and matter involves degradation from more to less organized states, and causes cycling of matter and origination of networks. Such dissipation affects the formation of structures, growth, development and evolution. Energy and matter cycle in ecosystems, with matter cycling necessary for the continuation of ecosystems on Earth because it is a closed planet with a finite quantity of material resources. Biological dissipation occurs during respiration, excretion, egestion, natural and predatory mortality and other activities. Relations of dissipation by organisms to size and temperature lead to relations for some life processes and certain ecological characteristics of organisms, supporting the theory of ecosystem size and structure. Matter dissipation is important, e.g., grazing mortality can speed primary production and nutrient dissipation can positively affect ecosystem production. Straskraba et al. (1999) investigate dissipation and suggest that ideas of trophic pyramids and ecological efficiencies should account for dissipation, and that ecological studies should focus more on fluxes than standing biomasses. The authors also note that detrital and microbial food paths are significant in ecosystems, and that dissipation of information relates to decreasing biodiversity. They suggest that present concerns over the environment can be explained as a dissipation-driven entropy crisis.

The equilibrium of an ecosystem may gradually become chaotic for many reasons. Mandal et al. (2007) examine thermodynamic properties in an ecological model shifting from ordered to chaotic, using a model with three species (phytoplankton, zooplankton and fish). Rate parameters are changed according to the change of size of the organisms. Different sizes of zooplankton are considered by increasing the grazing rate and consequently decreasing the half saturation constant of the organisms following allometric principles. The system exhibits different states (ultimately chaos) when gradual increments are made to the zooplankton grazing rate and decreases are made to the half saturation constant. Mandal et al. (2007) also investigate the high level of exergy, as a thermodynamic goal function, of systems at the edge of oscillation before entering the chaotic situation, and find that the high level of information indicates the system can coordinate the most complex behavior in these situations.

8.3.8. Exergy and Biodiversity

Biodiversity is a measure of species richness and heterogeneity, and has been assessed using exergy methods. Ecosystems normally exhibit significant flexibility to maintain their functions when faced with changes in external factors. New species are often able to take over if present species are not able to cope with changes in conditions imposed by external factors. Many ecological models are not able to describe such changes in species composition. The use of exergy as goal function in ecological models has been shown by Jorgensen (1992c) to incorporate into ecosystem models the flexibility of real ecosystems and the selection of species. Jorgensen argues that the application of exergy in modeling in some ways is a translation of Darwinian selection into thermodynamics, and he demonstrates for hydrobiology the shifts in species composition provided using exergy.

Benthic eutrophication often gives rise to qualitative changes in marine and estuarine ecosystems, such as shifts in primary producers. Such shifts are often followed by changes in species composition and trophic structure at other levels, and such modifications may over time determine a new trophic structure. Structural dynamic ecosystem models allow simulation of such changes, using goal functions to guide ecosystem behavior and development. Continuous optimization of model parameters in line with the ecological goal function then accounts for the selection of other species and food webs. Exergy has been somewhat successfully applied in structural dynamic models of shallow lakes (Marques et al.,

1997) with exergy optimized during ecosystem development so that an ecosystem self organizes towards a state of an optimal configuration of exergy. Exergy constitutes a system characteristic that expresses the natural tendencies of ecosystems to evolve and a good ecological indicator of ecosystem health.

The ecological significance of exergy has also been tested against biodiversity, which is an important characteristic of ecosystem structure. Specifically, Marques et al. (1997) examined the spatial and temporal relations between exergy and specific exergy and biodiversity along an estuarine gradient of eutrophication, and found that exergy and specific exergy and species richness decrease with increasing eutrophication, but that heterogeneity responds differently. Although biodiversity interpretations are somewhat subjective, it is suggested that exergy and specific exergy may be suitable alternative goal functions in ecological models and holistic ecological indicators of ecosystems integrity. The exergy of ecosystems can be determined from the biomass of the organisms in it or the thermodynamic information in genes.

Holling proposed a four-phase conceptual model of ecosystem dynamics as a guide for evaluating the impact on biodiversity of climate change (Hansell and Bass, 1998). The model includes exploitation and conservation, as well as destructive and renewal components, to explain the failure of many natural resource management programs. The model has two dimensions: connectivity and the amount of capital stored in the system.

8.3.9. Exergy and Climate Change

The impact of climate change on biodiversity can be assessed using the four-phase conceptual model of ecosystem dynamics proposed Holling (Hansell and Bass, 1998), as described in the previous subsection. However, the two dimensions in that model were found to be insufficient when compared with actual data, so attempts were made to revise the model and one such approach used exergy to improve the model. Specifically, Kay adjusted the dimensions of Holling’s model and changed one dimension to exergy stored and the other dimension to exergy consumed. This revision is observed to make Holling’s model agree better with observations and provide insight into the linkages between climate change and biodiversity. A different revision involved renaming one dimension as carbon stored and the other as nutrients (Hansell and Bass, 1998).

8.3.10. Exergy and Water Quality

The potential of exergy to provide a unified measure of water quality was investigated by Huang et al. (2007). That research was premised on the fact that applications of exergy to ecological evaluation, resource accounting and environmental impact assessment have shown it to provide a suitable indicator for ecological evaluation and a unified thermodynamic measure of resources and the environment. The study of water quality assessment using exergy determined that, compared with other existing methods, exergy accounting provides a single objective measure for water pollution.

Also, chemical exergy is proposed as a unified objective indicator for water quality, which avoids the subjectivity characteristic of conventional indicators (Chen and Ji, 2007).

For water quality evaluation, the authors consider 1) specific standard chemical exergy based on global reference substances, and 2) the specific relative chemical exergy with reference to a spectrum of substances associated with some specified water quality standard. Related concepts like carrying deficit and carrying capacity are embodied in the exergy terms. To illustrate the adaptability of chemical exergy-based indicators for water quality evaluation, water qualities of 72 rivers and 24 lakes from around the world are evaluated.

8.3.11. Exergy and Ecosystem Health and Quality

Ecosystem quality and health can act as goals for environmental management. For instance, exergy is demonstrated to be a useful measurable parameter for assessing the state of an ecosystem, and assessing of ecosystem health and the severity of anthropogenic damage (Silow and Mokry, 2010).

Specific exergy has been applied as an integrated index of environmental quality. Austoni et al. (2007), for example, explore the application of exergy and specific exergy on macrophytes as an integrated index to assess ecosystem health in coastal lagoons. Exergy and specific exergy are calculated as a function of the biomass multiplied by a weighting factor, which express the amount of information in the biomass. The authors evaluate weighting factors for 244 seaweed and seagrass species common to Mediterranean coastal lagoons. Also, the specific exergy is calculated for 71 sites in coastal lagoons of Southern France and found to agree well with existing classification schemes, suggesting that specific exergy provides an integrated index capable of synthesizing and complementing existing approaches.

Exergy measures have been used to assess ecosystem health, as measured by parameters like eutrophication. In many parts of the world, lakes and reservoirs are damaged and their biodiversity and resilience are decreased by eutrophication. Xu (1996) conducted an ecosystem health assessment of Lake Chao, a shallow eutrophic lake in China. Several measures were considered, including exergy and structural exergy, as well as trophic state index, diversity index and phytoplankton buffer capacity. The assessments provide appropriate information on the state of health of the Lake Chao ecosystem, and imply that the lake ecosystem is a typical eutrophic system with relatively poor health.

It is necessary in many of the approaches described in this section to calculate the exergy for organisms. Exergy can be estimated as the product of the biomass concentration and a weighting factor that accounts for the information carried by the organisms (Jorgensen, 2002a). The determination of the weighting factor for various organisms has been based on the number of coding and non-coding genes. The latter have been shown to be crucial for the control, maintenance and development of organisms. Results of genome projects have been used to determine weighting factors (Eichler and Sankoff, 2003). These values are useful in ecosystem health assessments, where exergy is used as an ecological indicator, i.e., an exergy index. Jorgensen et al. (2005) develop several indirect methods to determine weighting factors, accounting for such factors as age of the organisms, number of cell types, minimum DNA content, and ratio of non-coding genes to total number of genes (Mattick, 2003). The methods allow more weighting factors to be determined, which should improve their use in calculating exergy for the assessment of ecosystem health.

8.3.12. Exergy and Resources

Exergy provides a measure of resource quality or usefulness, and exergy destruction is a measure of resource degradation. Various facets of the relations between thermodynamics, including exergy and entropy, and resources have been reported recently (Bakshi et al., 2011). This book examines the use of energy and exergy in understanding resource use, the utilization of thermodynamics to account for resource use in general and in industries like manufacturing, and entropy production and resource consumption in life cycle assessments.

8.4. ECO-EXERGY

Eco-exergy is a modified form of exergy which measures a system's deviation from chemical equilibrium and which has been proposed as an ecological indicator. The exergy calculation provides a relative eco-exergy index. It is not possible to determine the eco-exergy of entire ecosystems, because they are far too complex to know all their details. Some eco-exergy indices have nonetheless been reported (Jorgensen and Nielsen, 2007). The exergy of detritus and of various organisms can be determined with eco-exergy, provided the concentration of detritus and the various organisms at chemical equilibrium are found (Jorgensen and Nielsen, 2007).

Eco-exergy and exergy destruction have been utilized to describe the development of an aquatic ecosystem. The respiration rate (energy used for maintenance) and the stored eco-exergy are determined for 26 different aquatic ecosystems (Jorgensen, 2007b), and the respiration rate is shown to peak for a given type of aquatic ecosystem (Odum, 1969). Increasing the ecological network and the information content of an ecosystem allows it to move further from thermodynamic equilibrium, i.e., to increase the content of eco-exergy. Plotting respiration versus eco-exergy storage in an ecosystem provides a useful tool and has been used for terrestrial ecosystems. The results of Jorgensen (2007b) support the "Ecological Law of Thermodynamics."

The two main differences between exergy and eco-exergy are that eco-exergy uses a changed reference state which may be more useful for ecological applications, and the contribution of information exergy taken into account. Susani et al. (2006) show that, when a shift is made from macroscopic to microscopic information storage, the exergy contribution due to information grows and becomes as much as three orders of magnitude greater than conventional exergy for complex living systems. Eco-exergy is seen to possess the capacity of holding information at the molecular level (DNA); this information differs among organisms.

Jorgensen (2006) proposes as ecological indicators for ecosystem development and health: 1) eco-exergy, 2) specific eco-exergy, which is the ratio of eco-exergy to biomass, and 3) ecological buffer capacities. Jorgensen shows that attributes for ecosystem development and descriptors of ecosystem health are accounted for by three types of ecosystem growth: biomass, network and information. Eco-exergy rises with increases in each of these growth forms, and is thus proposed as a good holistic indicator of ecosystem development and health. Supplementing eco-exergy with specific eco-exergy and buffer capacity provides information on the resistance of an ecosystem to perturbations.

8.5. EMERGY

8.5.1. Emergy-Based Methods

Emergy has been proposed as an objective function for ecosystems assessments. Emergy is defined as the solar energy required, directly and indirectly, to generate a flow or storage. The emergy concept includes the history, time and different processes that have occurred prior to the present state of the system, and thus is not a state property (i.e., a measure that is only dependent on the present state of the system). The emergy approach allows assessments and descriptions of self-organizing systems such as ecosystems (Bastianoni and Marchettini, 1997), and permits the assessment of large-scale systems like the biosphere, accounting for global energy and resource flows needed to support complex living systems.

Emergy accounts for energy quality using a transformity factor, which is found from the network as the number of solar equivalents needed to construct a given organism. The ecological network must be specified for emergy calculations.

Emergy analysis is a thermodynamic method from systems ecology which accounts for ecosystems. Although the method has proponents, it is not universally accepted, having encountered resistance from some physicists, economists and engineers.

8.5.2. Comparisons of Exergy and Emergy

Exergy analysis can be related to emergy analysis, and many comparisons and integrations have been reported. Both methods seek to represent the behavior of physical systems with cumulative energy input/output methods over space and time. Each method is preferred in certain application fields. The two approaches have been described as based on different paradigms and philosophies (Sciubba and Ulgiati, 2005), with emergy analysis focusing on resource flows for ecosystems, and exergy analysis providing insights like quantifying irreversibilities and the degree of matching between inputs and end-uses.

Aspects of emergy and exergy, including similarities and differences, are discussed by Bastianoni et al. (2007). They identify differences between energy-based emergy and exergy-based emergy, showing them to be proportional with the exergy equivalent of solar energy as the proportionality factor. The authors also demonstrate that emergy and transformity can be written as a function of exergy alone, and using partial efficiencies of the processes involved in a production system starting with solar energy and ending with a final product.

Exergy and emergy assessments have been compared and contrasted via case studies. One considers ethanol production from corn and its steps: corn production, transport and industrial conversion to ethanol. Exergy and emergy evaluations yield a set of performance indicators (Sciubba and Ulgiati, 2005).

Emergy and exergy can be considered complementary objective functions, and both can describe self-organizing systems like ecosystems (Bastianoni and Marchettini, 1997). The integration of ecological extremal principles is discussed for such quantities as exergy, emergy, power and ascendancy by Patten (1995).

Exergy calculations for higher organisms based only on traditional thermodynamics do not account for their organizational level, even though such information would seem necessary for comprehensive thermodynamic evaluations of ecosystems. A more rational approach founded on statistical thermodynamics is based on the thermodynamic information of genes. Another approach for exergy calculations of ecosystems including higher organisms parallels the method used for calculating emergy, and is based on the cost of free energy for an ecological network. The latter method is theoretically less sound than the first because it does not consider the increase of information due to evolution. The two methods reflect some of the differences between emergy and exergy, and results obtained using these approaches differ but are of the same order of magnitude (Jorgensen et al., 1995).

Sciubba (2009) has compared emergy and exergy analyses, and concluded that they are incompatible methods for the assessment of energy conversion systems, despite that fact that both approaches quantify resource consumption of systems with spatial- and temporal-integrated energy input/output methods.

8.5.3. Integrating Exergy and Emergy

Jorgensen et al. (2004) also have evaluated the emergy and exergy of genetic information and its biological carriers. The chemical exergy of genes is determined using detritus as the reference environment. The emergy used to construct and maintain biological organisms, which the authors consider carriers of genetic information, is evaluated using average global emergy input to the biosphere. Using generalized data for populations of organisms from bacteria to large mammals, emergy-exergy ratios for genes and solar transformities for biomass are calculated.

This ratio for gene maintenance provides a measure of the emergy required per unit exergy of genetic information. Generalized solar transformities for organisms are found for various biomass types, including those based on soil bacteria and mammals. The relation between the emergy costs of gene maintenance and the solar transformity of biomass suggests that the emergy costs of maintaining a biological carrier increase faster than the information carried as the complexity of the information carrier increases. The emergy to generate the genetic information contained in the biosphere today is estimated by Jorgensen et al. (2004).

The ratio of emergy to exergy for a flow provides the concentration of solar energy equivalent (emergy) required to maintain or create a unit of organization (exergy), and thus provides useful information on a system’s state (Bastianoni and Marchettini, 1997). This ratio measures how efficiently a system organizes itself or maintains its complexity and thus provides the environmental cost for the production of a unit of organization. The emergy/exergy ratio is determined for three coastal lagoons: 1) a control pond fed with estuarine water and cleaned water from a sewage treatment facility, 2) a waste pond fed with estuarine water mixed with more polluted (nutrient-rich) effluent and 3) a natural lagoon in a national park in Caprolace, Italy. The first two are built to purify sewage. The emergy/exergy ratio is lowest for the natural ecosystem and highest for the waste pond, and the ratio decreases over time for the control and the waste ponds, implying these systems are organizing via natural selection.

Bastianoni et al. (2006) examine the principles of maximization that have been connected with orientors developed to provide a holistic view of the development of ecosystems. Considering exergy and emergy flows in ecosystems, maximum emergy and maximum exergy principles are both found to have practical validity and to be applicable in a time sequence, with emergy maximization preceding exergy maximization.

8.6. CLOSING REMARKS

Relations between exergy and ecology are described and assessed. Exergy is shown to be useful in understanding ecology and ecological systems, and to be utilizable in their management. Exergy can help explain various ecological observations and phenomena, including ecosystem reactions, growth patterns, maturity, biodiversity and health. Related concepts are also of use, including emergy and eco-exergy. The relations and understanding provided through the exergy of ecosystems are potentially of great significance.

Chapter 9

CORRELATIONS BETWEEN EXERGY AND OTHER INDICATORS OF ENVIRONMENTAL IMPACT

OVERVIEW

Comparing the exergy of waste emissions and empirical measures to assess or control their potential environmental impact can identify important trends and patterns. Some of these are discussed in this chapter, including the notions that exergy may provide the basis for a tool for establishing emission limits that are rationally based and that exergy may have the potential to be, or be part of, a useful and meaningful indicator of potential environmental impact of a substance.

The exergy of waste emissions is compared to other measures to assess or control the potential environmental impact of emissions. Such comparisons can help identify trends and patterns that may:

- permit the exergy of a substance to be a useful and meaningful indicator of potential environmental impact, and
- provide the basis for a tool for establishing emission limits that are rationally based rather than formulated by trial and error.

9.1. BASIS OF CORRELATION

Based on a previous analysis (Gunnewiek and Rosen, 1998), the exergy of waste emissions is compared to other selected measures to assess or control the potential environmental impact of emissions, including

- air emission limits established by the government of Ontario, Canada, and
- two measures of “environmental costs” for emissions from fossil fuel combustion.

These comparisons help identify trends and patterns that may permit the exergy of a substance to be a useful indicator of potential environmental impact and consequently to be a tool for establishing emission limits that are rational rather than formulated by trial and error.

9.2. POLLUTION LIMITS

Air pollution limits in Ontario are covered by the provincial Environmental Protection Act. That legislation aims to ensure environmental conditions such that human health and the ecosystem of the Earth are not endangered. In Ontario, the Ministry of the Environment develops and implements environmental legislation for industry. Allowable air emission limits (i.e., pollutant mass per air volume averaged over a specified time), which must be achieved prior to discharge, are listed for numerous substances. Point of impingement (POI) air emission limits are determined considering the best available pollution control technology. The potential of a substance to impact the environment is evaluated by ten parameters:

- transport,
- persistence,
- bioaccumulation,
- acute lethality,
- sub-lethal effects on mammals,
- sub-lethal effects on plants,
- sub-lethal effects on non-mammalian animals,
- teratogenicity,
- mutagenicity/genotoxicity, and
- carcinogenicity.

Table 9.1. Environmental pollution costs for selected pollutants

Pollutant	Environmental pollution cost ($/kg pollutant)*
Particulates (including heavy metals**)	4.95
CO	4.46
NO_x	3.50
SO_2	3.19
CH_4	1.17
Volatile organic compounds	0.54
CO_2	0.036

* Values are reported in 2006 Canadian dollars. Environmental pollution costs are based on values from 1990 as measured by the Consumer Price Index for all products, with an adjustment applied to the dollar values to account for inflation in Canada between 1990 and 2006. Statistics Canada reports the adjustment factor as 1.401, which represents a 40.06% increase over the 16 year period or an average annual inflation rate of 2.13%.

** Includes lead, cadmium, nickel, chromium, copper, manganese and vanadium.

9.3. METHODS FOR COMPARISON

Two methods for developing environmental costs for air emissions are considered here:

- For air emissions from fossil fuel combustion, the cost is considered of removing pollutants from the waste stream prior to discharge to the environment. This cost can be related to the exergy of the pollution, and is referred to as the Removal pollution cost (RPC). The removal cost for a waste emission is evaluated as the total fuel cost per unit fuel exergy multiplied by the chemical exergy per unit fuel exergy, and divided by the exergy efficiency of the pollution removal process. The exergy efficiencies for removing pollutants from waste streams vary. Some sources indicate that exergy efficiencies are below 5% when removal involves mechanical separation. For simplicity, exergy efficiencies of 1% for all pollutants are used here.
- Estimate environmental costs of pollutant, which are referred to here as environmental pollution costs (EPCs). Such work is most advanced for atmospheric emissions from fossil fuel combustion. Environmental costs for some emissions have been estimated for Canada (see Table 9.1). Values for EPCs are based on quantitative and qualitative evaluations of the cost to correct or compensate for environmental damage, and/or to prevent a harmful emission.

9.4. PRELIMINARY CORRELATIONS

Preliminary relations have been discerned for POI air emission limits, standard chemical exergies, RPCs and EPCs. Environmental pollution cost appears to increase with increasing standard chemical exergy, and to increase at a decreasing rate with increasing percentage of pollution emission exergy.

The two measures considered here for the environmental cost of pollutants (RPC and EPC), although based on different principles, are of the same order of magnitude for a given pollutant. The RPC methodology is based on a theoretical concept, while the EPC methodology relies on subjective interpretations of environmental impact data. Thus, exergy-based measures for environmental impact may provide a foundation for rational environmental indicators and tools.

Environmental pollution cost and removal pollution cost are two different types of indicators, among the many existing and possible ones. EPC and RPC provide good examples for comparisons with exergy as indicators of environmental impact, since they are founded on different rationales. EPC is the environmental cost of a pollutant, based on such factors as the societal cost to compensate for damage and to prevent a harmful emission. RPC is the cost of removing a pollutant from a waste stream prior to discharge into the environment.

9.5. CLOSING REMARKS

By comparing the exergy of waste emissions to other measures to assess or control the potential environmental impact of emissions, important trends and patterns can be discerned.

First, the exergy of a substance is shown to have the potential to be, or be part of, a useful and meaningful indicator of potential environmental impact. Second, exergy is seen to provide the basis for a tool for establishing emission limits that are rationally based rather than formulated by trial and error and other empirical methods.

Chapter 10

EXERGY-BASED ENVIRONMENTAL AND ECOLOGICAL METHODS

OVERVIEW

Numerous exergy-based environmental and ecological methods are described, including reducing industrial emissions via increased exergy efficiency, design for environment and exergy, cumulative exergy consumption, exergy-based life cycle analysis, exergy-based industrial ecology, exergy-based ecological footprint analysis, exergy-based tolerances, resource renewability, EXCEM analysis, and extended exergy accounting. These methods assist in determining the environmental and ecological impacts associated with a system or process, and understanding and mitigating them. Although some of the methods extend other environmental techniques, many are developed originally around exergy concepts.

A description is presented here of existing analysis techniques which integrate exergy and environmental and ecological factors, and which have been developed by researchers over the last several decades.

10.1. REDUCING INDUSTRIAL EMISSIONS VIA INCREASED EXERGY EFFICIENCY

Progress toward sustainability in industry and other facets of society requires meaningful, practical and technically sound measures to aid decision making. Sustainability measures need to be able to assess the economy and ecosystem impacts of processes and products. Measures for assessing a process or product often account for material and energy inputs and emissions during process operation or product creation, and some measures consider the full life cycle of the process or product. Often measures involve multiple variables, which sometimes are conflicting.

10.1.1. Exergy and Efficiency Improvement

The United Kingdom committed through its government's 2003 Energy White Paper to develop a sustainable energy economy in the 21st Century, and to lead industrial countries in reducing CO_2 emissions, targeting reductions of 60% of 2003 values by 2050. Such targets are expected to require reductions in primary energy use to 45-75% of present levels, depending on the energy technologies employed, and the implementation of efficiency and conservation measures throughout the country (Hammond, 2004). Hammond notes that the insights provided by exergy analysis are important in identifying where improvement potential lies and generating policy advice on sustainability, although he notes that exergy should be applied in conjunction with information from other disciplines like economics, environment, ecotoxicology, etc.

Yi et al. (2004) propose an evaluation method for the environmental sustainability of industrial processes that uses exergy analysis to combine different material and energy streams and links exergy analysis with life-cycle assessment methods for the impact of emissions. The method provides hierarchical thermodynamic assessment measures having different levels of aggregation and integrates exergy, life cycle, input-output, economic and ecological aspects. These measures have been applied to ammonia production.

Giannantoni et al. (2005) developed an approach for improving energy systems design that considers multiple criteria:

- process-related, local-scale methods (energy, exergy and thermoeconomic analyses),
- environmental assessment methods, and
- economic methods (micro- and macro-economic and externality evaluations).

Process-related methods are applied first, in order to provide local-scale performance indicators able to suggest optimization procedures from a user-side point of view. Environmental evaluation approaches are then used to judge the overall environmental quality of the design, in the largest regional and biosphere scales. Finally, micro- and macro-economic evaluation approaches are applied in order to ascertain the soundness of the proposed solution as far as the economic return on the investment as well as global benefits to society are concerned. Cogeneration is used as a case study.

10.1.2. Exergy and Environmental Policy

From a broader perspective, projects have been carried out at Delft University of Technology and University of Twente to determine whether exergy analysis can be used in environmental policy development, especially for comparing alternative production chains. These studies investigate whether exergy's linkages with pollution and dispersion can be converted into a reliable tool on which policy decisions can be based, and explore how the environmental effects of processes can be linked to or expressed in terms of exergy changes.

10.2. Design for Environment and Exergy

Motivated by needs related to Design for Environment methods, the project referred to earlier entitled “Exergy as an Environmental Indicator” was undertaken (Connelly and Koshland, 1997, 2001a, 2001b). A major challenge when applying Design for Environment is the selection of an environmentally optimal process configuration from competing process designs. Existing methods for such analyses focus primarily on subjective ranking techniques, but researchers felt that exergy could be a less-subjective metric for Design for Environment assessments and investigated the practical application and adaptation of exergy analysis to specific problems associated with industrial material and energy flows (Connelly and Koshland, 1997, 2001a, 2001b).

10.3. Cumulative Exergy Consumption

The environmental impact of industrial processes can be assessed using cumulative exergy consumption, the exergy consumption accumulated over processes.

Zhu et al. (2005) extend cumulative exergy consumption for analyzing the environmental impact of industrial processes and for the treatment of emissions. They also proposed an environmental measure of equivalent cumulative exergy consumption based on an acceptable level. This measure can be used as part of an objective function for optimization of process parameters, and has been applied to heat pump distillation (Zhu et al., 2005).

A generalization of cumulative exergy consumption in resource analysis and ecological evaluation has been developed based on embodied exergy, which is the cosmic exergy consumed directly or indirectly in creating or sustaining a commodity or service (Chen, 2006). He considers cosmic exergy to be the fundamental natural resource for the ecosphere and society, as it provides the driving force of the Earth in the form of the radiation exergy difference between the sun and the cosmic background.

Cumulative exergy consumption has been extended to ecological cumulative exergy consumption so as to incorporate the contribution of ecosystems (Hau and Bakshi, 2004). This approach has been applied to industrial activity, showing the potential benefits of accounting for the contribution of nature. In essence, the approach extends exergy analysis to account for ecosystem products and services. Note that ecological cumulative exergy consumption is related to emergy, and equivalent under certain conditions, and the best features of emergy and exergy analysis can be combined.

Industrial and ecological cumulative exergy consumptions in the U.S. in 1997 were determined by evaluating flows of cumulative exergy in 488 sectors (Ukidwe and Bakshi, 2007). Ecological cumulative exergy consumption accounts for the exergy consumed in ecological systems in producing natural resources, and is analogous to emergy. Industrial cumulative exergy consumption evaluates the exergy of all natural resources consumed directly and indirectly by each economic sector. Exergy consumptions in nature can be evaluated using data from biogeochemical cycles. Consistent exergy units are used to allow various streams to be combined in the form of aggregate metrics that provide insights regarding the impact of economic sectors on the environment (Ukidwe and Bakshi, 2007).

Note that cumulative exergy consumption differs from cumulative energy demand, which has also been proposed as a predictor for the environmental burden of the production a commodity. Cumulative energy demand has been used to assess life cycle environmental impacts. The method has recently been compared with the results of six common environmental life cycle impact assessment methodologies for almost 500 commodities (grouped by metals, glass, paper and cardboard, organic and inorganic chemicals, agricultural products, construction materials, and plastics) (Huijbregts et al., 2010).

10.4. Exergy and Life Cycle Analysis

Life cycle assessment (LCA) is a cradle-to-grave analysis for investigating and reducing the environmental impacts of a system or process or product. LCA is used to assess and compare environmental impacts and to define the most environmentally critical phase in order to decrease the negative environmental effects of a product or a process (Curran, 2000).

Integrating exergy into LCA is important for identifying and understanding the underlying reasons for many environmental impacts, but the concept of exergy has only begun to be introduced into the LCA approach (Cornelissen, 1997; Dincer and Rosen, 2007). Extending LCA with exergy considerations can help efforts to reduce the depletion of exergy resources and emissions of waste exergy to the environment, and thereby can help improve sustainability. Exergetic life-cycle assessment (ExLCA) identifies the exergy utilization and destruction during the life cycle of a system or process or product. Overall exergy utilization and destruction cannot be properly assessed by examining only operation, but must consider all life stages from resource extraction to disposal.

Here, LCA is described and explanations are provided of the linkages between exergy analysis and LCA, the rationale for ExLCA, the ExLCA approach and methodology, applications of ExLCA and the advantages of ExLCA.

10.4.1. Life Cycle Analysis

Life cycle assessment is a technique for preventing pollution and improving environmental management and performance. In LCA, the entire life cycle of a product is considered (ISO, 1997), from natural resource extraction and plant construction to distribution and final product utilization and waste disposal. Material and energy flows and environmental impacts related to system construction, operation and disposal are accounted for with LCA. The technique allows environmental trade-offs associated with product or process alternatives to be characterized by assessing and comparing

- solid, liquid and gaseous environmental emissions and their environmental consequences, including human, animal and ecological effects, and
- impacts and trade-offs associated with environmental improvement measures.

The International Standards of Organization (ISO) 14000 series for life cycle assessment covers principles and framework (ISO, 1997), goal and scope definition and inventory analysis (ISO, 1998), life cycle impact assessment (ISO, 2000a), life cycle interpretation (ISO, 2000b) and requirements and guidelines (ISO, 2006).

Life cycle assessment consists of the following four main phases, as well as an interpretation step within all phases:

- *Goal and scope definition*. The system and aims of the LCA are identified in this phase, and the boundary of the LCA and the function considered are specified.
- *Life cycle inventory (LCI) analysis*. Energy and material inputs and outputs are determined for all flows across and within the system boundary, through all stages of the life cycle of the chosen product or service.
- *Life cycle impact assessment (LCIA)*. The environmental impacts of the material and energy flows are evaluated, sometimes by classifying them in terms of impact categories (e.g., global warming, ozone depletion, acidification, eutrophication) and characterizing their contributions to the impact categories. Various impact assessment methods have been developed: CML (Center of Environmental Science of Leiden University) 2001 (Guinée et al., 2002), Eco-indicator 95 (Goedkoop et al., 1996), EPS 2000 (Steen, 1999), IMPACT 2002+ (Jolliet et al., 2003), IPCC 2007 (Parry et al., 2007) and TRACI (Bare, 2002).
- *Life cycle improvement*. Conclusions and recommendations are developed to improve environmental performance, accounting for technical, economic, social and other factors. That is, reasonable ways are identified to decrease environmental, economic and other burdens.

For products having a major part of their life cycle in biological production systems like agriculture, assessments need to account for land use impact and land quality, and suitable indicators incorporating these factors have been developed based on ecosystem thermodynamics (Wagendorp et al., 2006). That work considers the possibilities in terrestrial ecosystems of any size for assessing land use impact directly by measuring the capacity of an ecosystem to dissipate solar exergy. Tseng (2004) has examined the application of thermodynamics to product life cycles more generally.

10.4.2. Exergetic Life Cycle Analysis (ExLCA)

By considering exergy, LCA can be extended to exergetic LCA (Granovskii et al., 2006b, 2007). Exergetic LCA has the same objectives as LCA, but also considers exergy flows and destructions and options for reducing exergy destructions and increasing exergy efficiency.

Environmental impacts associated with systems or processes can often be decreased by reducing exergy losses, i.e., increasing exergy efficiencies, thereby using less exergy resources and waste exergy emissions to the environment. Exergy losses occur during the lifetime of a product or a process, and reducing them helps improve sustainability (see Figure 7.1), as already discussed. Understanding of the relations discussed in Section 7.2 between exergy and the environment (waste exergy emissions, resource degradation, order destruction and chaos creation) illuminates the linkages between exergy and LCA.

Rationale of ExLCA

Conventional LCA is sometimes inadequate for the analysis of new and fundamentally different technologies due to a lack of inventory data about inputs and outputs and little knowledge about the potential human and ecosystem impacts. Unique and generalized indicators for these cases may be provided using exergy, partly because industrial and ecological processes and their life cycles are governed by the laws of thermodynamics (Bakshi and Ukidwe, 2006), and partly because exergy provides a means of addressing losses in the form of thermodynamic irreversibilities during the life cycle. ExLCA is consequently useful for evaluating the environmental impacts corresponding to exergy destructions over the life cycle of a process or system or product. These losses relate to exergy efficiencies, which measure the approach to ideality and indicate actual margins for improvement.

ExLCA Approach and Methodology

The main steps of ExLCA, which are similar to those for LCA, follow:

- Goal and scope definition. Same as for LCA.
- ExLCA inventory analysis. The inventory analysis is more extensive than that for LCA, in that exergy flows are also tracked and exergy destructions determined. The material and energy balances have to be closed, which is not always the case in LCA (Hermann, 2006). The exergy of flows is evaluated analytically with reported data.
- ExLCA impact assessment. The impacts on the environment of exergy flows, destructions and efficiencies are determined for the overall process or system and its parts. A limited impact classification phase is included.
- Life cycle improvement. Similar to LCA, but with the additional objective of reducing life cycle irreversibilities, i.e., exergy destructions over the life cycle, for the product or system or process (Hermann, 2006).

An ExLCA usually is preceded by an exergy analysis, which provides much of the necessary exergy-related data.

Advantages of ExLCA and Comparison with LCA

ExLCA complements LCA, and provides additional insights which can be beneficial (Bakshi and Ukidwe, 2006; Cornelissen and Hirs, 2002):

- ExLCA considers inputs and outputs (products, co-products, waste emissions) from the perspective of exergy.
- ExLCA focuses on both inputs and outputs, whereas LCA often focuses externally on emissions and their impacts. Complete mass, energy and exergy balances are necessary for ExLCA.
- The depletion of natural resources (e.g., energy resources such as fossil fuels, commodities such as mineral ores) is directly assessed with ExLCA as an exergy loss. Determining the depletion of natural resources is often difficult with LCA, since commodity and energy resources are viewed as distinct, and neglected in some LCA methods (omitting an important aspect of environmental impact).
- By accounting for all irreversibilities in a system or process, and its parts, ExLCA

addresses environmental impact more comprehensively than LCA and is thus more helpful for developing options to improve the efficiency and environmental impacts of systems and processes.

Consequently, exergetic life cycle assessment, although similar to LCA, can enhance the latter. Both methods seek to identify, quantify, characterize and decrease the overall environmental impact of a system or process or product, but ExLCA incorporates thermodynamic throughout the analysis. ExLCA is particularly useful for addressing the irreversibilities associated with the life cycle of a system or process or product in order to reduce the associated environmental impacts.

10.5. Exergy, Industrial Ecology and Eco-industrial Systems

10.5.1. Industrial Ecology

Industrial ecology is an approach to designing industrial systems that seeks improved environmental performance and sustainability by attaining a reasonable balance between industrial activity and environmental stewardship. Industrial ecology strives to make industrial systems behave more like ecosystems, where energy and materials are entirely recycled (except for the external supply of solar energy). According to Graedel (1996), industrial ecology “was conceived to suggest that industrial activity can be thought of and approached in much the same way as a biological ecosystem and that in its ideal form it would strive toward integration of activities and cyclization of resources, as do natural ecosystems.” Using the design of ecosystems to inform the design of industrial systems can, within the paradigm of industrial ecology, allow a better balance between industrial performance and ecological and environmental constraints.

Many of today’s industrial processes are linear or open systems, in which energy and material resources enter a system, move through several processes before exiting as wastes. One focus of industrial ecology is shifting industrial processes from linear systems to closed-loop systems where wastes become inputs for new processes (Graedel and Allenby, 2010; Frosch and Gallopoulos, 1989). This implies industrial systems should be designed with reduced mass and energy inputs and using energy sources that are renewable. Such designs reduce or eliminate waste energy and material emissions.

10.5.2. Industrial Ecology and Exergy

Industrial ecology methods can beneficially incorporate exergy to provide more powerful practical tools (Connelly and Koshland, 2001a, 2001b; Dewulf and Van Langenhove, 2002). Waste exergy emissions and exergy destructions, unlike energy losses, can account for the environmental impacts of energy utilization (Dincer and Rosen, 2005). Szargut et al. (2002) suggest that the cumulative consumption of non-renewable exergy provides a measure of the depletion of non-renewable natural resources. Connelly and Koshland (2001a, 2001b) suggest that the efficiency of fossil fuel consumption be characterized by:

- a depletion number, expressible as the ratio of the exergy destruction rate to the total exergy input rate, and
- a related exergy efficiency, defined as unity less the depletion number.

Zvolinschi et al. (2007) apply exergy sustainability indicators as a tool in industrial ecology, and have applied the approach to gas-fired combined cycle power generation. Kay (2002) treats systems of varying complexity using complexity theory, while accounting for exergy flows and considering applications in industrial ecology.

Dewulf and Van Langenhove (2005) integrate industrial ecology principles into a set of environmental sustainability indicators for technology assessment, based on the second law of thermodynamics. They present environmental sustainability indicators for the assessment of products and production pathways that take into account: resource renewability, emission toxicity, input of used materials, product recoverability after use, and efficiency.

10.5.3. Eco-industrial Systems and Exergy

Exergy analysis also has been applied to eco-industrial systems, allowing the thermodynamic characteristics of resource utilization to be understood by examining the material flow patterns in industrial systems (Li et al., 2006). Several indicators of resource-utilization efficiency and environmental-impact potential based on exergy are provided (e.g., system exergy depletion index, cycling ratio of material exergy), and their relations to each other and to industrial ecology are discussed.

10.6. EXERGY AND ECOLOGICAL FOOTPRINT

Exergy has been integrated into ecological footprint and environomics assessment methods. The ecological footprint indicator, including some exergy-based measures, has been reviewed by Wiedmann and Barrett (2010).

The aggregate indicator ecological footprint has been extended to embodied exergy ecological footprint, which shows the ecological overshoot of ecological systems, and applied to China for the period 1981-2001 (Chen and Chen, 2007).

Sciubba (2012) has critically assessed the use of exergy-based ecological indicators as a measure of the resource use footprint. He suggests that extended exergy accounting provides a good measure of the amount of primary exergy resources consumed in the life cycle of a material or immaterial commodity.

10.7. Exergy-Based Environmental and Ecological Tolerances

Exergy-based environmental and ecological impact measures have been proposed using tolerance limits, such as those exhibited by many living organisms and ecosystems to external changes before they themselves change. Based on the idea that exergy provides a kind of measure of potential for environmental and ecological harm, the exergy of an emission at its tolerance limit can be used as a measure of its potential environmental impact and as a measure of its environmental or ecological acceptability.

Such an approach involves a degree of subjectivity, as numerous tolerance limits can be hypothesized for a pollutant. Meaningful and realistic exergy-based tolerance limits for pollutants are needed, and developing such a variety of tolerance measures that are widely accepted can be difficult. But some basic tolerance measures may prove to be generally agreeable. Two examples follow:

- Tolerances can be linked to toxicity and health. For instance, limits can be established noting that otherwise healthy people become ill when concentrations in air exceed 0.8 mg/m^3 for SO_2 and 0.28 mg/m^3 for NO_2 (Hao and Ma, 2003).
- Tolerances for greenhouse gas emissions can be based on minimum allowable impacts from atmospheric global warming or climate change.

Different tolerance limits yield different allowable pollution levels, so tolerance limits must be careful decided upon.

10.8. Exergy-Based Renewability Assessment of Energy Sources and Carriers

Interest is growing in sustainable resources, i.e., resources that satisfy present needs without compromising the ability to meet future needs, and an important aspect of sustainability for resources is renewability. Technically, sustainability and renewability are difficult to quantify for energy resources. Traditional environmental assessments determine the environmental impacts of energy resource utilization, but the subjectivity involved in weighting the factors involved usually reduces their objectivity, rendering them of limited use in developing sustainability measures.

Traditional energy accounting is not useful for assessing the renewability of an energy resource. Determining an “energy yield” makes little sense since energy is conserved, unless we subjectively neglect certain forms of energy (Berthiaume and Bouchard, 1999). Also, the sustainability of life within a system depends not on the amount of energy present, but on the amount of useful energy available for performing useful or productive tasks. A meaningful energy-related yield calculation should indicate if there is a net gain or loss during the utilization of an energy resource and account for differences in energy quality, which can be assessed using exergy.

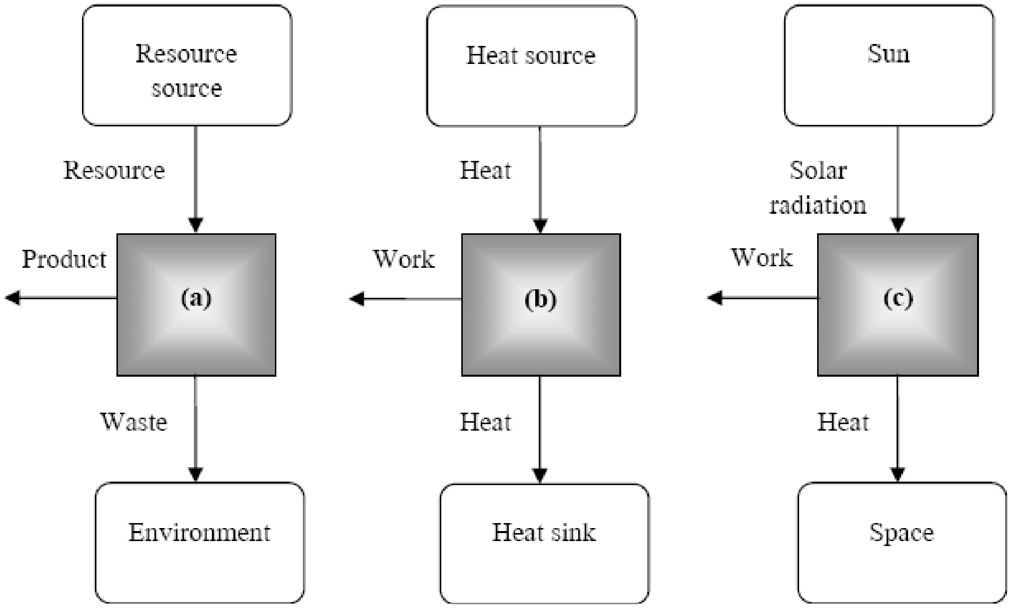

Figure 10.1. Production cycles. (a) General product generation from a resource; (b) thermodynamic cycle for a heat engine; (c) ecosystem using solar energy.

An approach for quantifying the renewability of energy resources and carriers using an exergy approach is described here. Included are discussions of the link between renewability and thermochemical cycles, as well as ideal behavior and the departure from ideal behavior caused by the consumption of non-renewable resources (NRRs). This section is partly based on the approach of Berthiaume et al. (2001).

10.8.1. Resource Renewability

Renewability of a resource is taken here to mean that regeneration mechanisms exist for the resource that maintain it without impacting the environment. Resources that are fully renewable normally return periodically to an initial state, i.e., the transformations which the resource undergoes are cyclic as is the case for many ecosystems. Resources are partially renewable when non-renewable resources are consumed in the processing of the renewable resource or in the restoration of the altered environment to its initial state.

10.8.2. Resource Renewability and Thermodynamic Cycles

A renewable source of energy can usually be utilized within natural or anthropogenic cycles. Three types are considered here:

- In general, resources are often used in cycles to generate a product, with waste exiting to the environment (Figure 10.1a).

- Thermodynamic devices often utilize cycles, e.g., heat engines generate work through heat interactions between hot and cold thermal energy reservoirs using a working fluid that undergoes several mechanical, thermal and chemical processes that make up a cycle (see Figure 10.1b). The working fluid returns periodically to its original temperature, pressure and chemical composition. Some cycles are thermomechanical and others thermochemical.
- An ecosystem may be considered as a succession of devices forming a natural thermochemical cycle where, overall, the work (or exergy) necessary to sustain life is acquired through energy exchanges between the sun and space (Figure 10.1c). During such natural cycles, matter can undergo thermal, mechanical and chemical changes, but is confined in the atmosphere, hydrosphere and lithosphere. A pseudo-equilibrium state is sustained, from the perspective of human-life time scales, permitting life to thrive. An ecosystem at this pseudo-equilibrium can be considered fully renewable.

Some resources are non-renewable since they are used by people faster than they are naturally produced. Fossil fuels, which represent accumulations of exergy over geological time scales, are a prime example.

Non-renewable Resource Consumption and Waste Generation

The processing of a renewable energy source usually involves the consumption of NRRs, i.e., resources which take an extremely long time to be renewed on a human time scale. When the exergy content of a NRR is altered through an irreversible process, the environment can also be considered to be altered.

Much research has been undertaken on exergy accounting of NRR consumption to quantify the environmental impact of processes. Szargut et al. (1988) proposed the concept of cumulative exergy consumption (CExC), the exergy used (including that in raw materials) to produce a product, as a measure of the environmental impact associated with a process. Cumulative exergy consumption can be extended by accounting for the exergy content of the products (Cornelissen, 1997; Berthiaume and Bouchard, 1999). Berthiaume and Bouchard (1999) define net exergy consumption (CNEx) as follows:

$$\mathrm{CNEx} = \mathrm{CExC} - Ex_{\mathrm{P}} \tag{10.1}$$

where Ex_{P} denotes the exergy of products. CNEx accounts for all exergy consumed, from the extraction of raw materials through to manufacture of the final product, and may be considered the minimum work required to restore a degraded NRR to its initial state by means of a series of ideal (reversible) transformations.

For example, consider automotive gasoline produced by petroleum refining. For this process, CExC = 42.4 MJ/kg (Szargut et al., 1988). If the gasoline, which has a specific exergy of 35.6 MJ/kg, is not combusted, CNEx = 42.4 – 35.6 = 6.8 MJ/kg, but CNEx = CExC = 42.4 MJ/kg if the gasoline is consumed in a process.

The exploitation of a renewable energy source may also generate wastes due to insufficient recycling of matter, and work must be consumed to treat these wastes to prevent environmental damage. When the amount of waste is relatively small and much land area is available (for extensive treatment), such work may be provided by nature, e.g., in a wetland. But NRRs are consumed in waste processing for intensive treatment, such as in aerated lagoons or activated sludge systems.

Consequently, work may be needed to restore degraded NRRs to their initial states during resource processing and/or waste treatment. This restoration work W_R may be estimated through CNEx accounting as follows:

$$W_R \cong \mathrm{CNEx}_p + \mathrm{CNEx}_w \tag{10.2}$$

where subscripts p and w account for resource processing and waste treatment, respectively.

Renewability Indicator

When work W_P is produced from a renewable cycle, but NRRs are consumed, the restoration work W_R for the degraded NRRs should be taken into account in measuring the extent to which the overall process is renewable (see Figure 10.2). A renewability indicator I_r can be expressed based on this idea as follows:

$$I_r = \frac{W_P - W_R}{W_P} \tag{10.3}$$

Values of the renewability indicator can be positive or negative. $I_r < 0$ for a process which needs more work for restoration than it produces, while $I_r = 0$ for a process where the work produced and restoration work are equal. Also, $0 < I_r < 1$ for a partially renewable process (see Figure 10.2), and $I_r = 1$ for a fully renewable process, i.e., for $W_R = 0$.

The renewability indicator accounts for renewability factors (cyclic process, environment restoration, NRR consumption) in terms of exergy and integrates them in a unified manner.

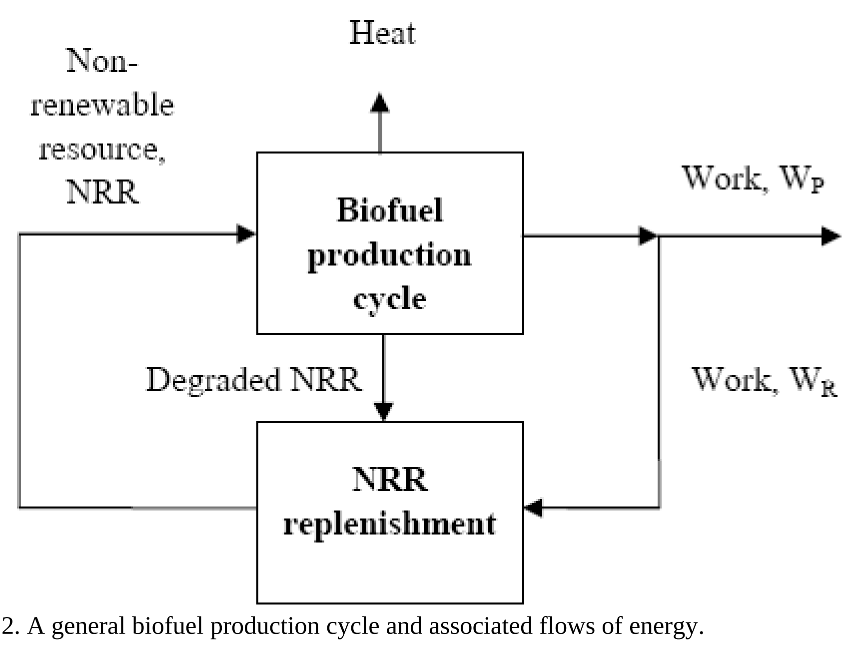

Figure 10.2. A general biofuel production cycle and associated flows of energy.

10.9. EXCEM ANALYSIS

EXCEM (exergy, cost, energy and mass) analysis is a methodology that focuses on the four key parameters represented by its name for evaluating devices and processes. It was developed by the author (Rosen, 1986; Rosen and Dincer, 2003c) to form the basis of a unified methodology for thermodynamic, economic and environmental decisions, and to assist in design. EXCEM analysis combines exergy with other factors that relate to the environment and ecology (mass and energy). That is, EXCEM allows important commodities related to the environment and ecology, such as resource inputs and waste outputs, to be tracked. EXCEM analysis also accounts for flows of costs, enhancing the usefulness of the method. Thus EXCEM analysis can be useful for the environmental and ecological assessments of systems and processes and, by extension, it can also assist in improving environmental performance.

The rationale of an environmentally focused EXCEM analysis is that an understanding of system or process performance requires examination of the flows of exergy, cost, energy and mass into, out of and at all points within a system. The rationale for EXCEM analysis is illustrated in Figure 10.3. Balances can be written for each of the EXCEM quantities. Of the quantities represented by EXCEM, mass and energy are conserved while exergy and cost are not. Exergy decreases or remains constant, while cost increases or remains constant.

The framework for an EXCEM analysis is illustrated in Figure 10.4, emphasizing the conservation of energy and mass and the non-conservation of exergy and cost. The EXCEM framework is extended in Figure 10.5 for a process in which inputs of exergy, energy and mass are separated into commodities and drivers (e.g., fuels), while inputs of cost are separated into cost commodities and operating costs. Similarly, outputs of EXCEM quantities are divided into products and wastes. The subdivision in Figure 10.4 assists environmentally based uses of EXCEM analysis by making the tracking of losses in the forms of waste emissions as well as internal destructions (for the case of exergy only) more straightforward.

EXCEM analyses of numerous engineering processes have been carried out, demonstrating that the EXCEM analysis methodology can provide valuable insights into performance and efficiency, economics, and potentials for environmental damage for systems and processes. The exergy-related aspects of EXCEM are often the most informative.

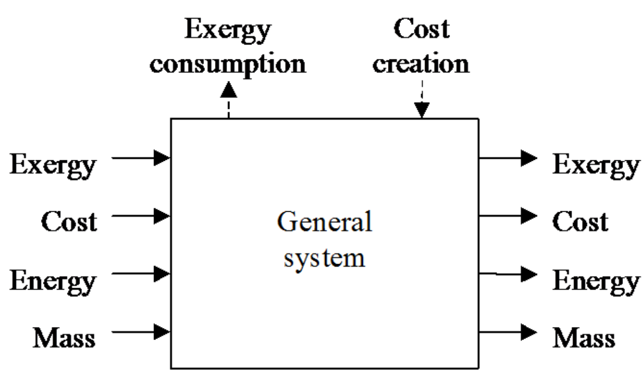

Figure 10.3. EXCEM analysis for a general system. Exergy consumption and cost creation are shown with dashed lines to denote that they do not actually enter or exit the system boundary.

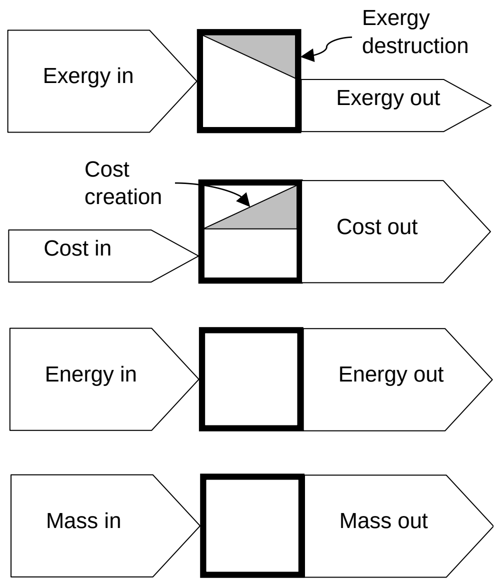

Figure 10.4. Flows of each EXCEM quantity for a process or system (box in each diagram). Line thicknesses for flows are proportional to magnitudes. Shaded regions denote non-conserved quantities.

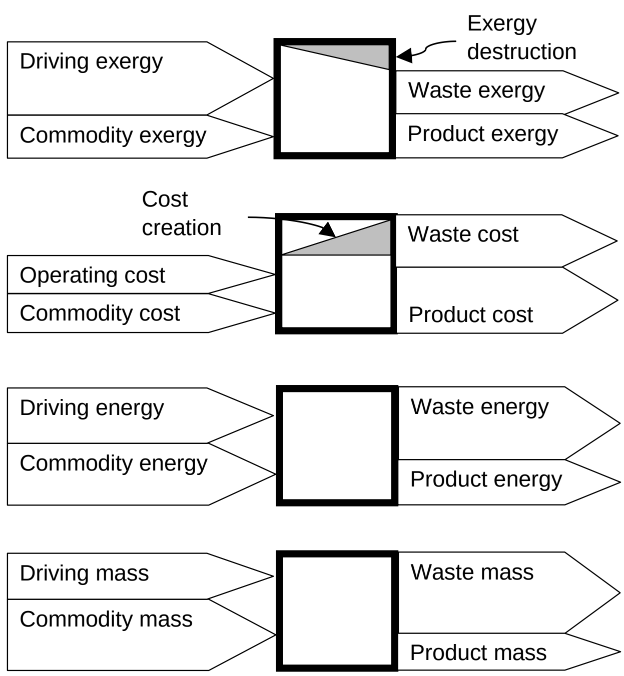

Figure 10.5. Flows of each EXCEM quantity for a process or system (box in center of each diagram). Line thicknesses for flows are proportional to their magnitudes, and the non-conservation of exergy and cost are designated by shaded regions. Inputs of exergy, energy and mass are separated into commodities and drivers (e.g., fuels). Inputs of cost are separated into cost commodities and operating costs. Outputs are separated into products and wastes for all EXCEM quantities.

10.10. Extended Exergy Accounting

Extended exergy accounting (EEA) facilitates assessments of a complex system by determining the cost of a commodity based on its resource-base equivalent value, as opposed to its monetary cost (Sciubba, 2004). The method includes equivalent exergy flows for labor, and capital and environmental remediation costs, and accounts for the unavoidable energy dissipations in any productive chain. Sciubba (2004) argues that EEA properly resolves matters difficult to address in a purely monetary manner. Sciubba (2001b) also uses exergy through extended exergy accounting to evaluate environmental externalities, following an approach that provides a general framework for including effluent clean-up techniques in designs. The approach also provides a basis for assessments of future pollution reduction technologies and policies. The method has been applied to cogeneration (Sciubba, 2001b).

Extending exergy accounting and thermoeconomics with environmental factors improves the analysis and design of energy processes and systems (Sciubba, 2001a). The approach allows direct quantitative comparisons of factors like labor and environmental impact and externalities. Sciubba argues that the approach

- permits some issues that are difficult to address with a purely monetary theory of value to be resolved without introducing arbitrary assumptions, and
- is a natural development of the economic theory of commodity production, which it extends by accounting for the unavoidable exergy consumption (or energy dissipation) in the production chain.

The premise of extended exergy accounting is that, while exergy and monetary costs may have the same morphology since both represent the quantity of resources required to produce a given output, their structures may differ, allowing for different optimal designs. The approach recognizes that a cost theory should be formulated based on exergy destruction because it conveys the idea that resources must be consumed to produce a product or service.

Sciubba (2003, 2004) also proposes extended exergy accounting as a cost analysis method for energy systems using a resource-based quantifier. The method allows the costing of production chains, and utilizes the Leontiev-type input-output technique adopted in most costing theories, including thermoeconomics. Rather than monetary units, a resource-based quantifier (extended exergy) is employed. This quantifier allows labor and financial costs to be linked to an equivalent resource consumption, thereby expressing the total exergy consumption required to produce one person-hour of work or one monetary unit of currency circulation. Environmental remediation costs are taken into account by determining the equivalent cumulative exergy expenditure required to achieve zero impact. Extended exergy accounting thus finds the resource-based value of a commodity, which is not necessarily its monetary cost, thus enabling energy planners to perform more comprehensive and meaningful assessments. The technique complements such other tools as life-cycle assessment and environmental footprint analysis and incorporates some elements of those and other environmental methods like cumulative exergy analysis and emergy analysis (Odum, 2002).

Belli and Sciubba (2007) also propose extended exergy accounting as a general method for assessing the primary resource consumption of social and industrial systems.

10.11. Exergy-Based Environmental Assessments of Regions, Countries and Sectors

Since energy resources are used for transportation, space heating, industrial operations and other processes, concerns about the finite nature of energy resources and the impacts of energy utilization on the environment can only be addressed if energy resources are utilized advantageously in countries and regions as well as their sectors.

The energy utilization of a country or region is conventionally analyzed by examining the flows of energy through various sectors of the economy. This analysis is useful in certain circumstances, but can be misleading when used to analyze how effectively energy is utilized. Energy analyses often indicate the main inefficiencies to be in the wrong sectors, quantify waste emissions and other losses in a misleading manner, and tend to determine a technological efficiency higher than actually exists (Rosen, 2011). One outcome of that work is the suggestion that financial investments in energy research and development should be related to or guided by exergy rather than energy measures.

Many believe that to properly assess how well a country or region utilizes its energy resources, an examination of the flows of exergy, rather than energy, through the sectors is required (Rosen, 1992, 1993; Dincer and Rosen, 2007; Moran et al., 2011). Given that exergy can provide a measure of environmental or ecological impact potential, assessments using this understanding can be useful at the national, regional and sectoral levels. Exergy and its environmental and ecological relations are described for regions like countries.

Note that the methodology outlined in this section is illustrated subsequently (see Chapter 27) for two regions: the province of Ontario, Canada and the United States.

10.11.1. Exergy Analysis of Regions, Countries and Sectors

Exergy assessments of regional, national and global energy systems as well as sectors of an economy can reveal significant insights useful for identifying efficiency limits and margins for improvement, as well as resource consumptions, waste emissions and other losses. By describing the use of energy resources in society in terms of exergy, important knowledge and understanding are gained, and areas are identified where large improvements can be attained by applying measures to increase efficiency and where large losses and emissions occur that may be indicators of potential environmental impact (Reistad, 1975, 1980; Wall, 1990; Dincer and Rosen, 2007). Such insights can help identify and prioritize areas in which technical, environmental and other improvements should be undertaken in regions and countries, and in economic sectors.

Energy efficiency η and exergy efficiency ψ for the principal processes in regions are usually based on standard definitions, as provided in Section 5.6:

$$\eta = \text{(Energy in products)/(Total energy input)} \tag{10.4}$$

$$\psi = \text{(Exergy in products)/(Total exergy input)} \tag{10.5}$$

Table 10.1. Exergy-to-energy ratios for some common energy commodities

Energy commodity	Exergy-energy ratio
Shaft work	1
Electricity	1
Steam at 600°C	0.6
Water at 90°C	0.2
Heat at the reference-environment temperature, T_o	0
Chemical energy for most hydrocarbon fuels	0.85-1.1

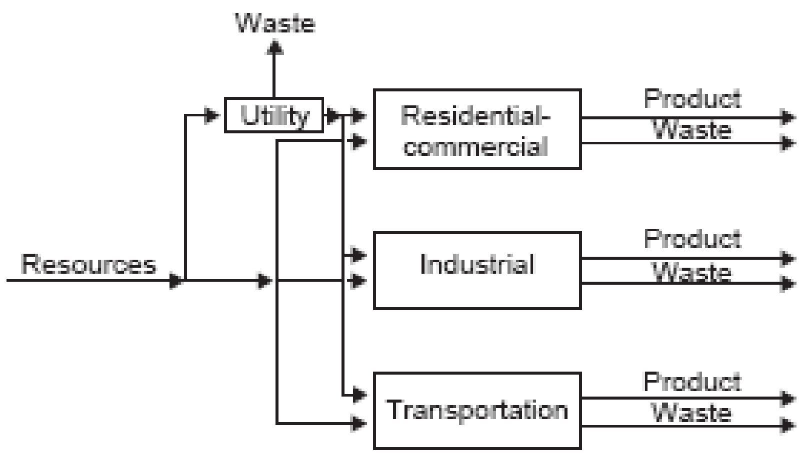

Figure 10.6. Model of a region or country or the world, showing flows of resources like energy from inputs to product and waste outputs.

Several processes dominate the energy utilization in regions and countries: work production, electricity generation, heating, cooling and kinetic energy production. The exergy of an energy resource can for simplicity often be expressed as the product of its energy content and an exergy-to-energy ratio for the energy resource, which can be viewed as a quality factor. Exergy-to-energy ratios for some energy forms are listed in Table 10.1.

10.11.2. Methodology for Assessment of Links between Exergy Losses and Environmental and Ecological Impacts for Countries, Regions and Sectors

Although many suggest links between environmental and ecological impact and exergy factors (Dincer and Rosen, 2007), little work relating exergy efficiencies or inefficiencies to environmental and ecological impact for countries or regions has been reported.

A methodology is described in this section to assess and compare the environmental and ecological impact for a system with the energy and exergy inputs and losses of that system. The methodology involves four main steps:

- *Modeling*. The country or region is modeled. One such model is shown in Figure 10.6, where four main economic sectors are considered: residential-commercial (including institutional), industrial, transportation and utility (electrical and other). In analyzing such a system, the energy and exergy flows through the overall system and its sectors are evaluated, and efficiencies and losses are determined. These quantities help identify environmentally or ecologically sensitive wastes and resource extractions. To model and assess the individual sectors, each is broken down into its main categories and the categories are divided into specific types. For instance, the residential and commercial sector can be broken down into residential, commercial and institutional categories, and several types of processes can be considered for each category (e.g., space heating, space cooling and domestic hot water heating). Energy and exergy efficiencies can be determined for each of the processes occurring in the system, the main ones of which are heating (electric, fossil fuel, other), cooling (electric, thermal, other), work production (electric, fossil-fuel), electricity generation and kinetic energy production. The industrial sector is particularly complex due to the range of processes occurring in it (Brown et al., 1985). A reference environment which simulates the natural environment must be used to evaluate exergy commodities for environmental and ecological assessments.

- *Efficiency evaluation*. Energy and exergy efficiencies and inefficiencies are evaluated for the region or country, and for its sectors, by determining flows of inputs and outputs. For energy or exergy, the inefficiency is the difference between one (or 100% on a percentage basis) and the corresponding efficiency. The fraction of the total energy loss for a sector is considered the *perceived inefficiency*. This quantity is believed by many not to represent a true picture of inefficiency, despite public perception (Gaggioli, 1983; Dincer and Rosen, 2007). The fraction of total exergy loss (internal destructions plus waste emissions) for a sector is considered the *actual inefficiency* or *real inefficiency*. Note that it is important to break down exergy losses into destructions and emissions, as each has a different meaning in terms of potential for environmental or ecological impact. This term *actual inefficiency* is justified, since the value measures how far the efficiency deviates from the ideal efficiency and is therefore meaningful. The perceived and actual inefficiencies for a sector can be determined as follows:

$$\text{Perceived inefficiency} = 1 - \eta \tag{10.6}$$

$$\text{Actual inefficiency} = 1 - \psi \tag{10.7}$$

where η denotes the energy efficiency and ψ the exergy efficiency. The perceived and actual inefficiencies can also be determined for a sector. For sector *j*, for instance, we can write

$$(\text{Perceived inefficiency})_j = (\text{Energy loss})_j/(\text{Energy input})_j = 1 - \eta_j \tag{10.8}$$

$$(\text{Actual inefficiency})_j = (\text{Exergy loss})_j/(\text{Exergy input})_j = 1 - \psi_j \tag{10.9}$$

where the subscript j denotes sector j.

- *Impact assessment*. Environmental and ecological impacts, based on many measures, are identified and assessed for the sectors and subsequently interpreted.
- *Improvement*. Environmental and ecological impacts for the sectors are compared with the energy and exergy inefficiencies, and with the breakdown of exergy losses by consumptions and emissions, to help assess where potential for environmental impact is greatest. This information, in conjunction with other factors like economics, is used to help recommend environmental and ecological measures.

10.11.3. Interpretation of Linkages between Exergy Losses and Environmental and Ecological Impacts for Countries, Regions and Sectors

The preceding discussions can be interpreted so as to illustrate the variations with environmental performance of

- exergy efficiencies for regions and countries, and
- margins for efficiency improvement, i.e., actual inefficiencies.

This interpretation can be made while accounting for circumstances and settings of a region or country, where factors and attributes that characterize the region for purposes of this discussion include environmental constraints, energy resource availability, energy resource costs, and availability of funds. Other related factors are also considered.

Typical variations in exergy efficiencies and the corresponding margin for efficiency improvement for regions and countries with two sets of realistic environmental standards, as well as other characteristics, are presented in Figure 10.7. Countries and regions with major concerns for environmental protection as well as high energy costs and availability of funds are likely represented by the second bar, while those with low concerns for environmental protection as well as low energy costs and lack of funds are likely represented by the rightmost bar. These cases likely bracket other regions and countries, i.e., those having some but not all of major environment concerns, high energy costs, availability of funds, etc. The hypothetical case of ideal efficiency is also shown in the figure, both for comparison and because an exergy efficiency of 100% always specifies ideal but unattainable thermodynamic behavior and entails low environmental impact since the process is reversible.

Several other important points can be observed in Figure 10.7:

- High exergy efficiencies are usually observed in countries and regions with strict environmental constraints or emissions limits, circumstances that foster high efficiency, funding for efficient technologies, high energy costs, readily available export markets for energy commodities, etc. Low exergy efficiencies are usually observed in countries and regions with lax environmental constraints, lack of funding for efficient technologies, low energy costs, lack of awareness of efficient technologies, and lack of a sufficiently educated and skilled workforce.
- The ultimate margin for efficiency improvement is seen to be the difference between the ideal exergy efficiency of 100%, which applies to ideal processes or devices, and the actual exergy efficiency. An awareness of this limit helps in establishing realistic

targets for efficiency improvement, which affect environmental performance directly. Countries and regions with lower rather than higher exergy efficiencies have greater margins for efficiency improvement, which are characterized by actual inefficiencies.

- When energy-related factors change, countries and regions tend to respond, in line with their interests. For instance, strengthening of environmental regulations often causes countries and regions to introduce measures that lead to increased efficiency. Since a rational approach is provided by exergy methods, appropriate efficiency targets should be established based on exergy, as confusion and waste can result if efforts to determine appropriate efficiency targets are based on energy.

Specific regions or countries are not easily identified in Figure 10.7 because their characteristics are usually more complicated than the two simple cases shown. Nonetheless some generalities and trends, which likely apply in numerous cases, can be pointed out:

- Developed or industrialized countries tend to fall into the middle category in Figure 10.7, since they usually have strict environmental restrictions and laws, high energy costs, readily available mechanisms for exporting energy resources, and funding for efficient conversion and utilization technologies. The wealth of such countries often makes them require or expect energy resources to be used cleanly and efficiently.
- Although the characteristics of countries with developing economies vary greatly, many less developed countries fall into rightmost category in Figure 10.7 due to relatively less strict environmental laws. Also, energy resources are often less affordable (i.e., energy costs are high as a proportion of gross domestic product or average income per capita) and obtaining funding for efficient technologies is difficult. This behavior is partly related to the focus of such countries on meeting basic needs and/or developing economically and in other ways.

The ideas discussed here are somewhat confirmed in many countries and regions, where significant disparities exist in factors like environmental regulations and energy costs. In much of Europe and Asia, for example, energy prices are roughly double those in North America, and higher exergy efficiencies are observed.

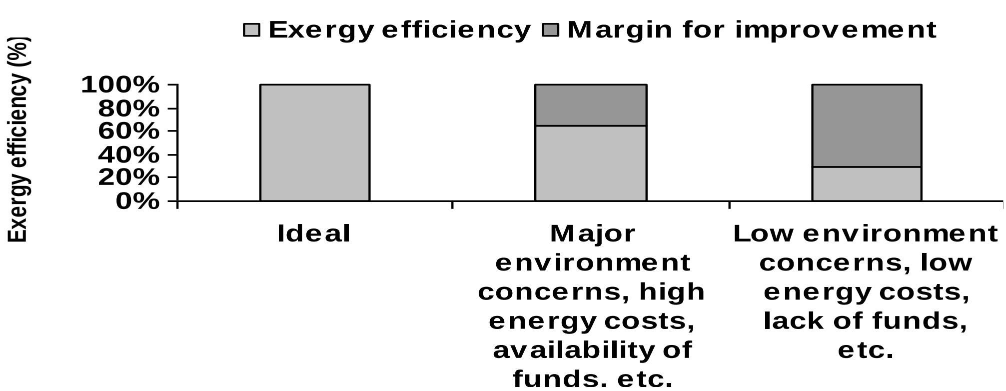

Figure 10.7. Comparison of exergy efficiencies and margins for improvement (or actual inefficiencies) for regions and countries having various environmental and other attributes.

In the future, the ideas discussed here suggest that countries and regions are likely to move towards higher exergy efficiencies due to factors like environmental limitations, energy price increases (long-term), and resource scarcities particularly because of growth in developing economies (e.g., China and India).

In comparing environmental and ecological impacts with energy and exergy losses for regions and countries, it appears that the perceived inefficiency is treated as significant and the actual inefficiency is of less importance or overlooked. If actual inefficiencies are used in establishing targets, efforts focus on the sectors with large margins for improvement, usually fostering improved environmental performance. Such information can assist government and public authorities in improving environmental and resource regulations.

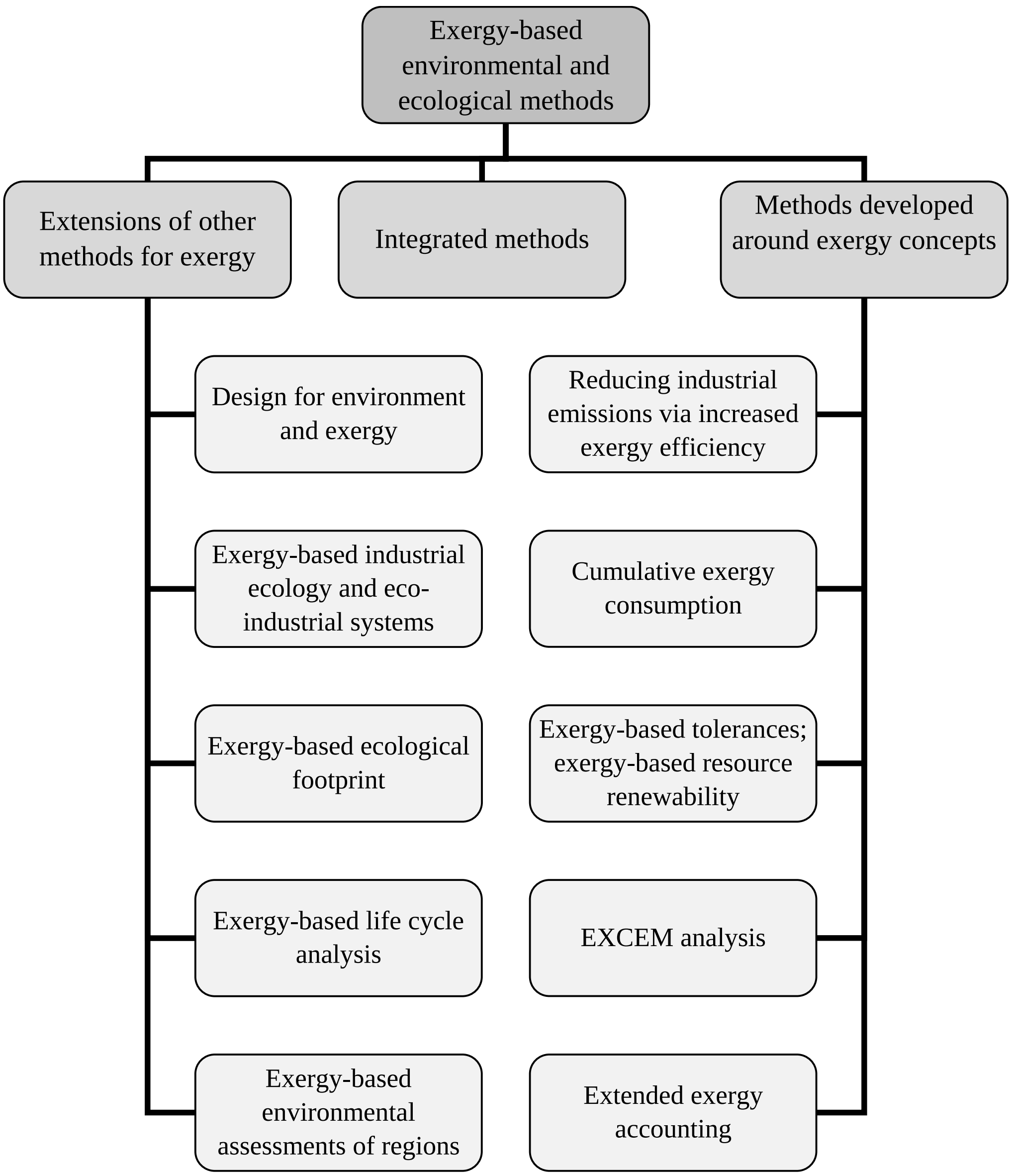

Figure 10.8. Various exergy-based environmental and ecological methods.

10.12. INTEGRATED METHODS

Some researchers have suggested that environmentally-oriented design, improvement and optimization can be made more effective by using multiple methods, integrated appropriately. For instance, exergy-based LCA and cumulative exergy consumption can be integrated, and sometimes yield superior results to using either in isolation. Also, Cortés and Rivera (2010) have developed an optimization method incorporating exergoeconomics, thermoeconomics and pinch analysis, and claim the methodology can lead to higher efficiencies and lower operational costs than when individual optimization methods are applied separately.

10.13. CLOSING REMARKS

In this chapter, various exergy-based environmental and ecological methods developed over the last several decades are described, including reducing industrial emissions via increased exergy efficiency, design for environment and exergy, cumulative exergy consumption, exergy-based life cycle analysis, exergy-based industrial ecology, exergy-based ecological footprint analysis, exergy-based tolerances, resource renewability, EXCEM analysis, and extended exergy accounting. The methods help in determining and improving the environmental and ecological impacts associated with a system or process. Some of the methods are extensions of other environmental techniques (e.g., exergy-based LCA and exergy-based industrial ecology), while others are developed around exergy concepts as original methods. The methods are summarized in Figure 10.8.

Methods based on extending the linkages between exergy and environmental and ecological impacts to economics (e.g., concepts such as carbon exergy taxes) also exist, and are presented in the next chapter.

Chapter 11

EXTENDING EXERGY, ENVIRONMENT AND ECOLOGY RELATIONS TO ECONOMICS

OVERVIEW

Numerous approaches and techniques which extend exergy and environmental and ecological methods to account for economics are described, including those relating exergy with environomics, environmental economics, environmental costs and taxation, economics and industrial ecology, ecology and economics, constraints to economic growth, economic sustainability. These approaches utilize the characteristic of exergy that makes it a potential indicator of environmental impact, and/or include the costs associated with environmental impact and protection in exergy-based economic assessments. Trade-offs involving exergy, environmental, ecological and economic parameters, and optimization, are also discussed.

As noted in earlier chapters, exergy has been used in assessments of environmental impact, resource depletion, ecology and sustainable development, and has been related to environmental methods like industrial ecology. The ties between exergy and the environment and ecology can be extended to economics. This can be accomplished in several ways:

- The costs associated with environmental impact and protection can be included in the economic portion of an exergy-based economic assessment.
- The characteristics of exergy that allow it to be an indicator of potential environmental impact can be incorporated in exergy-based economic assessments.

By extending exergy and environmental and ecological methods to account for economics, techniques can developed that permit one to reduce life cycle costs and thereby to find the most appropriate device or process for a given application. This can be accomplished while reducing environmental effects, for given prevailing economic conditions. Applications of these ideas are starting to increase. For instance, Meyer et al. (2009a) utilize exergoenvironmental analysis to evaluate the environmental impact of energy conversion systems, while Valero et al. (2009) have introduced exergoecology, a methodology which utilizes exergy in evaluating natural fluxes and resources. Tsatsaronis (2011) has recently examined exergoeconomics and exergoenvironmental analysis in detail.

Approaches and techniques that extend exergy and environmental and ecological methods to account for economics are described in this chapter.

11.1. EXERGY AND ECONOMICS

Exergy is a useful concept in economics (Tsatsaronis and Valero, 1989). Wall (2003), for instance, states that exergy is crucial not only to efficiency studies but also to cost accounting and economic analyses, and goes on to note that costs should reflect value and, since value is not generally associated with energy but with exergy, assignments of cost to energy lead to misappropriations, which are common and often gross. It has been further pointed out that exergy possesses an intrinsic and direct correlation with economic values (Sciubba, 2001a). Thus exergy allows the rational evaluation of the value of fuels and resources, as well as the efficiencies of processes and devices and their inefficiencies (including internal exergy consumptions due to dissipation or irreversibility and external waste exergy emissions), yet exergy also facilitates the determination of the costs associated with thermodynamic losses and the values and costs of the outputs and accumulated quantities of processes and devices.

Consequently, using exergy content as a basis for cost accounting can help in determining the real costs of producing commodities and in pricing such products. In addition, exergy can help evaluate economic viability and profitability. The benefits and drawbacks of exergy-based economic methods, as well as the relations between exergy and economics, have been investigated (Rosen, 2002b, 2011).

Exergy can interface broadly with economics. In microeconomics, exergy can be combined with cost-benefit analyses to improve designs. In macroeconomics, exergy provides a basis for increasing efficiency, or reducing resource utilization and losses, or reducing environmental damage. These objectives can be accomplished with, for example, exergy-based incentives or exergy taxes.

11.1.1. Exergy and Economic Methods

Georgescu-Roegen (1971) is often cited as a pioneer in the field of the thermodynamics of economics and the father of the discipline. Since that time, numerous analysis techniques which integrate exergy and economics have been developed (Gaggioli and El-Sayed, 1989; El-Sayed and Gaggioli, 1989; Dincer and Rosen, 2007; Rosen, 2011). These exergy-based economic methods include:

- thermoeconomics and exergoeconomics (Yantovskii, 1994; El-Sayed, 2004; Gogus, 2005; Sciubba, 2001a; Tsatsaronis, 1993, 1994, 1996, 2007a, 2008; Lazzaretto and Tsatsaronis, 2006; Valero, 2006; Valero et al., 2002, 2006a, 2006b; Kim, 2010),
- second-law costing,
- exergy-based cost accounting,
- exergy-based pricing (Bandura and Brodiansky, 2001; Wall, 1997),

- EXCEM (exergy, cost, energy and mass) analysis (Rosen, 1986; Rosen and Dincer, 2003c), and
- analysis based on the ratio of thermodynamic loss to capital cost (Rosen, 1986, 1990b, 1991, 2002b).

Most exergy-based economic analysis methods have several common characteristics, in that they:

- combine exergy and economics to help achieve thermodynamic and economic objectives, and
- recognize that exergy, not energy, is the commodity of value in a system, and they consequently assign costs and/or prices to exergy-related variables.

Goals of most exergy-based economic techniques include one or more of the following:

- assessment of the economic feasibility and profitability of a system, in part by determining the actual costs of products and appropriate prices, and
- evaluation of the appropriate allocation of economic resources so as to optimize the design and operation of a system.

The use of thermoeconomics for system improvement has been investigated by many, e.g., El-Sayed and Tribus (1983). Further, the optimization aspect embedded within the latter point is a particularly important application of exergy-based economic techniques (Hua et al., 1989). Optimal designs need to meet multiple requirements, including performing as specified by design data and satisfying all constraints, and displaying the most advantageous characteristics under a given set of conditions. Noting that optimization can be challenging, Sciubba (2001a) points out that optima are not always expressed by a well-posed mathematical objective function and instead often involve vague or incomplete optimization design criteria which are often fuzzy.

Four main categories of exergy-based economic methodologies can be identified, depending on which of the following forms the basis (Tsatsaronis, 1987): exergy-economic cost accounting, exergy-economic calculus analysis, exergy-economic similarity number, and product/cost efficiency diagrams. Reistad and Gaggioli (1980) have developed methods for available energy costing. Further information on methods of economic analyses based on exergy have been reported in textbooks (e.g., Kotas, 1995; Szargut et al., 1988; Bejan, 1982; Rosen, 2011), in critical reviews and comparisons (e.g., Tsatsaronis, 1987; Kotas, 1995; Bejan, 1982; Rosen and Dincer, 2003a, 2003b, 2003c), and in numerous research articles.

11.1.2. Other Exergy and Economic Approaches

Exergy more broadly can help in optimizing engineering designs and in making operating decisions. Wall (2003) describes exergy-based concepts and methods for analyzing and optimizing energy systems, including exergy-economic optimization as well as exergy utility diagrams and life cycle exergy analysis.

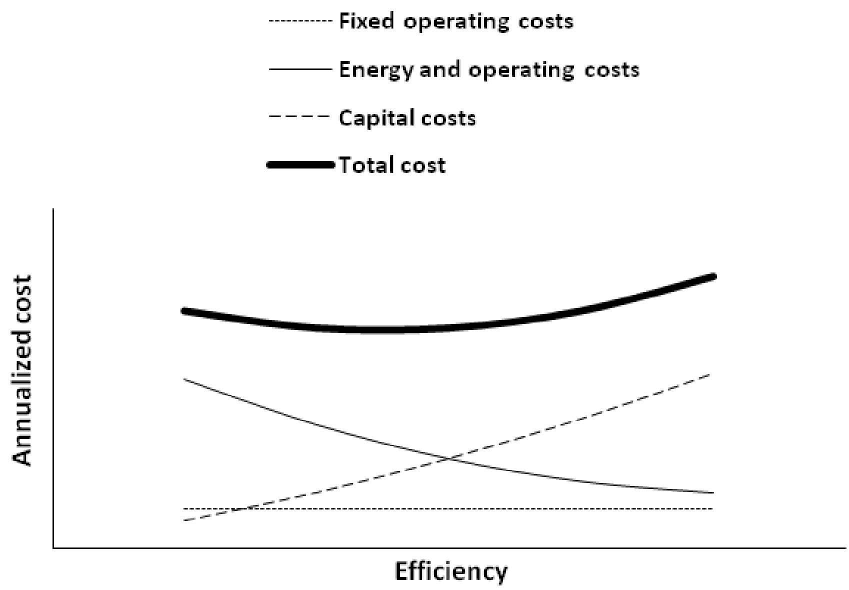

Figure 11.1. Variation with efficiency of the annualized total cost for a process and its main component costs.

Tsatsaronis and Park (2002) have examined the relation between exergy destructions and investment costs in thermal systems.

Jaber et al. (2004) have attempted to link thermodynamic concepts, including exergy and entropy, to price-driven economic systems. Related investigations involve modeling the economic order quantity with an approach based on the second law of thermodynamics (Jaber et al., 2006) and using entropy cost to evaluate the economic order quantity for repair and waste disposal (Jaber and Rosen, 2008). Also, Nuwayhid et al. (2006) consider diffusion-like economic commodity flows from a thermodynamic perspective, by modeling a commodity flow as a quasi-thermodynamic irreversible process. In that work, which supposes that the laws of thermodynamics can explain the process of commodity diffusion, a coupling relationship between commodity price and quality is derived.

11.1.3. Exergy and Economic Optimization

The total annualized cost of a process is typically viewed as the sum of its capital costs, energy and other operating costs, and fixed costs. Typically, as the efficiency of a process increases, its annualized capital costs increase while its annualized energy and other operating costs decrease, as shown in Figure 11.1. At some efficiency, the annualized total cost often exhibits a minimum. The minimum annualized total cost can be sharp, indicating that it is sensitive to variations in efficiency, or relatively flat. Although typically based on energy, the efficiency in Figure 11.1 can lead to added insights when based on exergy. Then, optimization activities that seek minimum annualized total costs are often better informed.

Figure 11.1 helps illustrate economic optimization but tends to be oversimplified. Costs usually cannot be determined as precisely as suggested by the curves in Figure 11.1 because equipment is normally produced in discrete sizes so the cost often varies in a stepwise manner rather than continuously, and the costs of some components are interrelated. Also, capital, energy and other operating costs normally vary temporally and spatially.

Optimization involves numerous parameters which must be considered simultaneously. The optimization of components individually usually does not yield an optimum for an overall system, and trade-offs are common in design. The efficiency can be altered by modifying design parameters such as device operating conditions or types or configurations.

Sometimes the optimum condition shown in Figure 11.1 is not desired:

- A lower efficiency may be chosen if funds for capital costs are not available, or if it is uncertain if the process will be retained long enough for its lower operating costs to offset the correspondingly higher capital costs at the optimum.
- A design may be selected that operates at higher efficiency than that corresponding to the minimum annualized total cost if reducing the energy costs is a priority (e.g., to enhance energy security).

The ideas in the preceding paragraph can be extended to capital costs and thermodynamic losses. A trade-off between thermodynamic losses and capital investments is evident when losses are based on exergy (see Figure 11.2), but not in general when losses are based on energy. An appropriate balance between capital costs and exergy losses appears to be present in successful systems (see top of Figure 11.2). Imbalances can occur if excessive capital is invested to reduce exergy losses or if excessive exergy losses are tolerated to save capital (see middle of Figure 11.2).

11.2. ECONOMICS AND EXERGY-BASED ENVIRONMENTAL AND ECOLOGICAL METHODS

A pristine environment is ordered, with clean water, soil and air as well as abundant plants and animals. The decrease in order associated with allowing pollutants to disperse randomly through the environment appears to be correlated to environmental impact. A corollary is that the exergy destruction as a clean environment degrades to a chaotic one is a measure of the minimum work (or exergy) that is required to clean up, that is to reinstate the original condition of the environment. Exergy has also been applied as a tool for assessing the health of ecosystems, in part because it has been demonstrated to provide a useful and measurable indication of the state of an ecosystem and the severity of anthropogenic damage. Although based on thermodynamics, exergy correlates well with various ecosystem goal functions. Ecology-based applications of exergy have recently been reviewed (Silow and Mokry, 2010), including ecological modeling and natural ecosystem monitoring.

Designing efficient and cost-effective systems, which meet environmental requirements, is one of the foremost challenges facing engineers. Given the world’s finite natural resources and large energy demands, it is important to understand mechanisms which degrade energy and resources and to develop systematic approaches for improving systems while simultaneously reducing environmental impact.

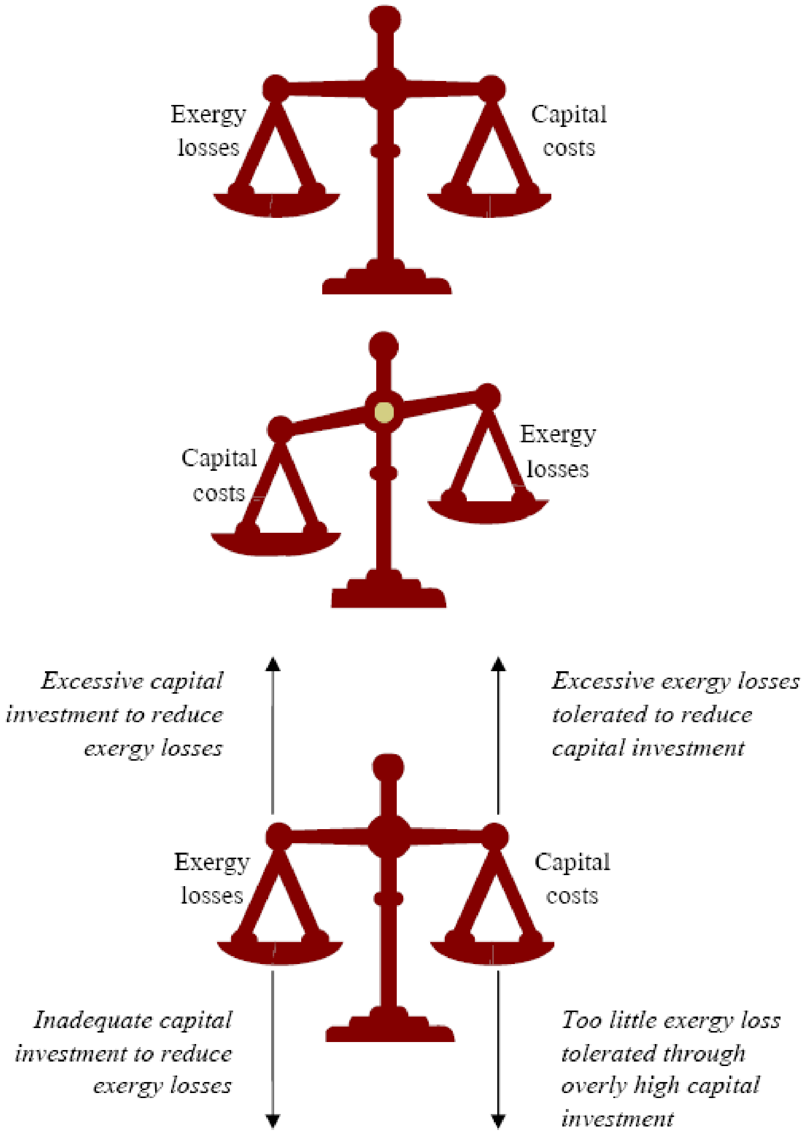

Figure 11.2. Relations between capital costs and exergy losses (but not energy losses).
Top: balanced system where appropriate trade-off is made between capital costs and exergy losses; middle: imbalanced system where excessive capital is invested to obtain overly efficient equipment; bottom: possible measures to rectify imbalances (increase capital investments to reduce exergy losses or accept greater exergy losses to reduce capital outlays).

11.2.1. Exergy, Environomics and Environmental Economics

Several researchers have investigated exergy and environmental economics (Edgerton, 1982). A methodology known as environomics has been developed for analyzing and improving energy-related systems by simultaneously taking into account energy, exergy, economic and environmental factors (Frangopoulos and von Spakovsky, 1993). Sciubba (2005) proposes exergoeconomics as a thermodynamic foundation for rational resource use.

Lazzaretto and Toffolo (2004) show how energy-system designs can be optimized using separate objectives relating to energy, economics and the environment. This multi-criterion optimization is argued by those authors to be advantageous to single-objective thermoeconomic optimization and a two-objective energy and economic optimization. An environmental impact objective function is expressed in cost terms by weighting carbon dioxide and nitrogen oxide emissions according to their unit damage costs.

Tonon et al. (2006) propose a comprehensive analysis method based on energy, exergy, economic and environmental factors. Environmental emissions are considered and performance indicators developed, providing useful information about system performance and possible areas of improvement.

A method for performance evaluation under maximum ecological and maximum economic conditions is described by Tyagi et al. (2007). In this method, the ecological function is represented by the power output divided by the entropy generation rate, and the economic function by the power output divided by the total cost.

11.2.2. Exergy, Environmental Costs and Taxation

Valero et al. (2009) propose "physical hydronomics" as a new discipline for assessing environmental costs related to water. Those authors state that degradation of water bodies such as rivers and lakes can be quantified with physical hydronomics, permitting a cost structure for ecological systems to be developed based on scientific principles rather than price policies or other subjective factors. The method provides a guide for assessing environmental costs included in the European Water Framework Directive.

Several proposals for exergy-based taxes have been put forth, from various perspectives:

- By considering the economic value of exergy in fuels, Reistad (1970) suggests an air-pollution rating in which the air-pollution cost for a fuel is estimated as either the cost to remove the pollutant, or the cost to society of the pollution, i.e., the tax which should be levied if pollutants are not removed from effluent streams.
- Including taxation effects into pricing structures is suggested by Szargut (2005).
- A thermoeconomic method to increase the efficient use of exergy resources based on a carbon exergy tax is proposed by Santarelli (2004), with the intent of promoting the efficient use of exergy resources. That author feels that the method, which evaluates the cost of exergy destroyed and rejected of an energy system, and which is connected with the CO_2 emissions, can improve the economic suitability of systems by permitting them to make better use of exergy.
- To reduce carbon dioxide emissions, carbon taxes have been proposed that represent a monetary charge linked to emission intensity. *Borchiellini et al. (2000) propose a* carbon exergy tax, which is a carbon tax based on an efficiency penalty for a given energy system that represents the cost of the exergy destroyed in the system and the cost of the exergy rejected to the biosphere with wastes. The efficiency penalty is

coupled to the carbon dioxide emission and thereby to the exergy efficiency of the system. The carbon exergy tax represents a charge on carbon dioxide emissions.

11.2.3. Exergy, Economics and Industrial Ecology

Valero et al. (2010) discuss the application of thermoeconomics to industrial ecology, which involves the transformation of industrial processes from linear to closed loop systems so that material wastes are minimized or avoided. A systematic and general approach for waste flow integration is developed by extending the thermoeconomic cost formation of wastes to consider their use as inputs to other processes. The combination of thermoeconomics and industrial ecology assists in identifying possibilities for integration and efficiency improvement and quantifying of the resulting benefits, and determining fair prices based on physical roots. The methodology is demonstrated for a power plant, a cement kiln and a gas-fired boiler (Valero et al., 2010).

11.2.4. Exergy, Economics and Emergy

Thermoeconomic methods focus on the thermodynamic and economic aspects of the conversion of fuels and other inputs to an energy system into products. To better understand the environmental implications of an energy system, that focus can be extended to the biosphere, by including processes involved in the formation of the system inputs (material and energy flows and the devices in which they are processed). This extended focus is the basis of “emergy” analysis (Odum, 2002). Thermoeconomic and emergy analyses were recently compared and contrasted by Lazzaretto (2009), who points out that, while both seek to allocate costs of resources input to a system among products, they differ substantially.

11.2.5. Exergy, Ecology and Economics

Exergy-based economics has been linked to environment and ecology. For example, an ecological economics perspective of economic development and environmental protection is provided by Rees (2003). Ecological economics interprets the environment-economy relation in terms of the second law of thermodynamics and exergy, which view economic activity as a dissipative process. Producing economic goods and services consumes resources, including exergy, from this perspective. Economic growth consumes sources of high-quality energy/matter from nature, and disorders and homogenizes the ecosphere. Pristine ecosystems are typically observed to be ordered and have high exergy while damaged ecosystems are disordered and have low exergy. Rees (2003) notes that the ascendance of humanity has consistently been accompanied by an accelerating rate of ecological degradation, especially pollution and loss of biodiversity and complexity in natural systems, and observes that economic development (i.e., “material economic growth”) unavoidably conflicts with environmental protection. He further notes that growth-oriented global development is fundamentally incompatible with long-term ecological and social sustainability. More broadly, money is considered “social exergy” by Spiegelman et al. (2007).

11.2.6. Exergy and Constraints to Economic Growth

The principles of mass and energy conservation indicate that raw material inputs to processes are not consumed, but instead ultimately return to the environment, from which they were extracted, as wastes. If the Earth is treated as a closed system, the concepts of exergy and entropy yield different economic implications, suggesting that constraints are imposed on economic growth because processes utilize high-exergy (or low-entropy) raw materials such as fuels and high-grade minerals, and discard low-exergy (or high-entropy) wastes. Since the Earth is an open system that receives large quantities of high-exergy (or low-entropy) solar radiation, energy resources may be adequate to sustain activity in the solar system over time, although non-renewable natural resources like metal ores and fossil fuels may eventually be exhausted.

Ayres (1998) links economics and the second law in what he refers to as "eco-thermodynamics." He argues that the economic significance of the second law lies in the fact that exergy is not conserved and is a useful measure of resource quality and quantity that is applicable to energy and materials. Ayres states that exergy is a factor of production like labor and capital, and that exergy has strong implications on economic growth theory, especially in assessments of the role of technical progress.

11.2.7. Exergy, Economics and Sustainability

Some authors shift the focus of exergy-based economic methods that encompass environmental factors to sustainable development. In 1977, before sustainability had been coined as a term, Wall suggested that exergy is useful for the management of resources to meet needs for sustainable development. Also, Ferrari et al. (2001) discuss the integration of thermodynamics and economics for exergy-based indicators of sustainable development.

Exergy and entropy are applied to the steady-state economy by Honkasalo (1998), so as to develop a model for sustainable development at the macro-economic level. The approach combines resource depletion with pollution and focuses environmental protection on reducing degradation losses. As a consequence, industries are able to seek alternative possibilities for environmentally sound production processes and products. The method can be applied as a conceptual tool that permits companies to set environmental goals and establish corresponding environmental programs.

11.2.8. EXCEM and Economics

The EXCEM analysis methodology described in the previous chapter (see Section 10.8) already incorporates an economic factor, in that one of the key factors of focus in the methodology for evaluating devices and processes is cost. EXCEM allows important commodities related to the environment and ecology, such as resource inputs and waste outputs, to be tracked. EXCEM analysis also accounts for flows of costs, enhancing the usefulness of the method.

Figure 11.3. Trade-off between exergy efficiency and environmental and ecological impacts. A balance is observed between environmental and ecological impacts and exergy efficiency, but imbalances can occur if exergy efficiency is targeted to be too high in order to reduce environmental and ecological impacts or if excessive environmental and ecological impacts are tolerated to allow an inefficient system or process to be utilized.

Figure 11.4. A common trade-off between capital cost investments and environmental and ecological impacts. A balance is often observed between environmental and ecological impacts and capital costs, but imbalances can occur if too much capital is spent to reduce environmental and ecological impacts or if excessive environmental and ecological impacts are tolerated to reduce costs.

11.2.9. Extended Exergy Accounting and Economics

Extended exergy accounting analysis, as described in the previous chapter (see Section 10.9), incorporates an economic factor. Specifically, it includes the cost of a commodity based on its resource-base equivalent value, as opposed to its monetary cost. Extended exergy accounting can be used to evaluate environmental externalities, and to assess pollution reduction technologies and policies rationally.

11.3. Trade-offs Involving Exergy, Environmental, Ecological and Economic Parameters

In general, trade-offs are made among exergy, environmental, ecological and economic parameters, as it is normally not possible to satisfy all objectives concerning these parameters simultaneously. One way of visualizing the trade-offs is to extend Figure 11.2 beyond efficiency and costs. This is done in Figure 11.3, which illustrates the trade-off between exergy efficiency and environmental and ecological impacts associated with a process or system. This trade-off suggested by the diagram is not rigorous, but rather indicates that there is in the real world an appropriate balance between exergy efficiency and environmental and ecological impacts, and that increases in exergy efficiency normally tend to reduce the environmental and ecological impacts.

The trade-off illustrated in Figure 11.3 can be further extended to relate capital cost investments with environmental and ecological impacts. In Figure 11.4, the trade-off between capital cost investments and environmental and ecological impacts, for instances where a capital cost investment increases exergy efficiency directly (e.g., the cost is aimed at adding a clean-up technology) or indirectly (e.g., the cost enhances the process, including its efficiency). The trade-off suggested by the diagram is certainly not rigorous, and does not include situations where a capital investment is made to enhance a technology even if it decreases exergy efficiency (e.g., enlargening the screen of a large-screen television so that it is more appealing). But Figure 11.4 does suggest that there is in the real world an appropriate balance between capital cost investment and environmental and ecological impacts, and that increases in capital cost often tend to reduce environmental and ecological impacts.

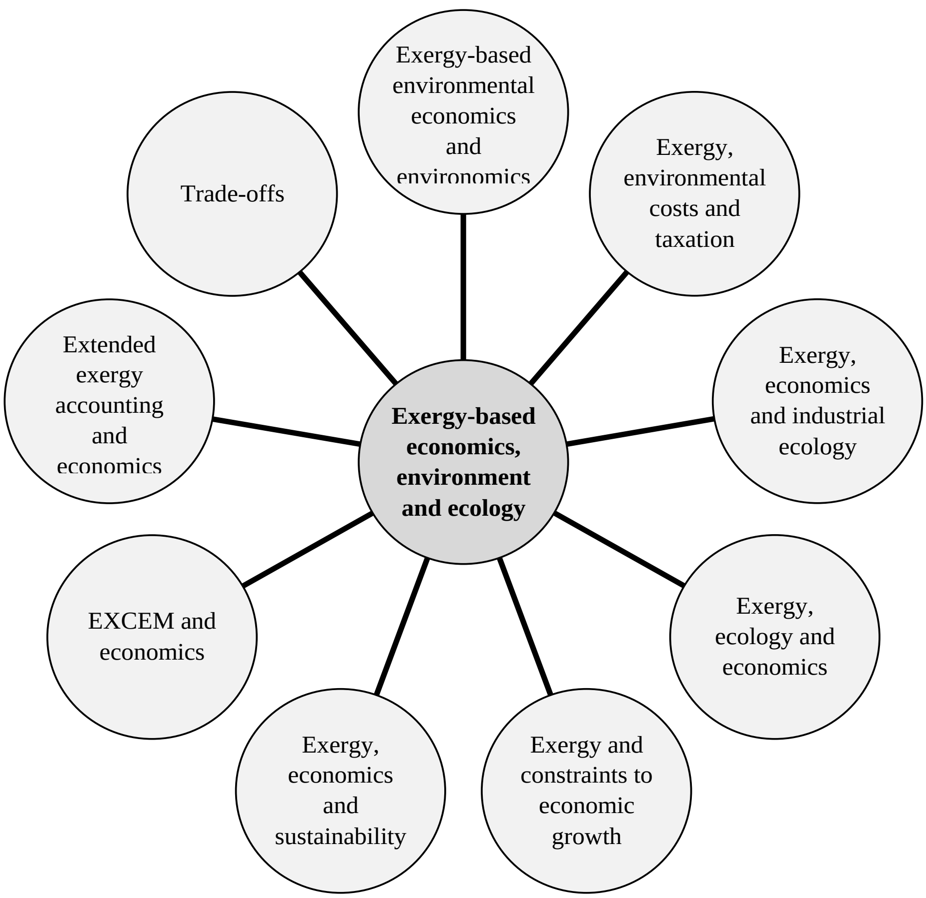

Figure 11.5. Various approaches and techniques which extend exergy and environmental and ecological methods to account for economics.

Optimization procedures are often used to seek the best combinations of parameter values, in line with specified objectives and constraints, thereby finding the appropriate trade-off among parameters for a given situation.

11.4. CLOSING REMARKS

Various approaches and techniques which extend exergy and environmental and ecological methods to account for economics are described in this chapter, and summarized in Figure 11.5. These include the relation between exergy and environomics, environmental economics, environmental costs and taxation, economics and industrial ecology, ecology and economics, constraints to economic growth, and sustainability. Trade-offs involving exergy, environmental, ecological and economic parameters are also discussed and, to provide a broader context, the relations between exergy and economics are covered. This material suggests that the characteristic of exergy that allows it to be a potential indicator of environmental impact can be incorporated in exergy-based economic assessments, and that the costs associated with environmental management and protection can be included in the economic portion of an exergy-based economic assessment.

PART III: APPLICATIONS

Chapter 12

EXERGY APPLICATIONS

OVERVIEW

Numerous applications of exergy analysis to improve efficiencies of processes and systems have been reported, ranging from simple to complex processes, and from technology improvements to national and global assessments. Application areas include industrial operations and sectors such as transportation, as well as power generation, cogeneration, trigeneration, heating, refrigeration, chemical processing, fuel production, separation, distillation, desalination, energy storage, and others.

Numerous applications of exergy analysis to improve efficiencies of processes and systems have been reported, ranging in size from simple to complex processes. As a consequence of the growing acceptance of exergy, specialized textbooks on exergy and related methods have been written (Dincer and Rosen, 2007; Bejan, 1982. Kotas, 1995; Moran, 1989; Szargut, 2005; Szargut et al., 1988; Brodyanski et al., 1994; Sato, 2005) and general thermodynamics texts have increasingly included material on exergy (Bejan, 2006; Moran et al., 2011). Additionally, the *International Journal of Exergy* was launched and has been thriving for almost a decade. Many exergy applications can be found in these.

12.1. ENGINEERING SYSTEMS

Many applications of exergy analysis to engineering systems have been reported over the last several decades or so.

Some examples follow:

- electricity generation using conventional technologies like fossil fuel and nuclear power plants (Rosen, 2001; Dincer and Rosen, 2007; Rosen and Dincer, 2003b; Rosen and Tang, 2007, 2008) as well as advanced technologies like fuel cells (Cownden et al., 2001), pressurized fluidized bed combustion (Rosen and Horazak, 1995) and geothermal plants (Dipippo, 1994; Dincer and Rosen, 2007),

- cogeneration of electricity and heat (Rosen et al., 2005; Dincer and Rosen, 2007; Abusoglu and Kanoglu, 2009a, 2009b),
- thermal processes (Bejan, 1982; Kotas, 1995; Szargut et al., 1988), including drying (Dincer, 2002; Dincer and Rosen, 2007), industrial heating (Rosen and Dincer, 2004a), solar grain drying (Oko and Nnamchi, 2012), district heating (Ozgener et al., 2004), cooling (Kanoglu et al., 2004), heat pumps (Dincer and Rosen, 2007), cryogenics (Dincer and Rosen, 2007), dehumidification (Van Den Bulck et al., 1988), psychrometric processes (Dincer and Rosen, 2007), and fluid flow (Bejan, 1982),
- chemical and metallurgical processes (Szargut et al., 1988; Sato, 2005), including petrochemical refining and processing (Dincer and Rosen, 2007),
- renewable energy utilization (Koroneos et al., 2003), including solar, wind and geothermal (Lee, 2001; Dipippo, 1994),
- industrial processes (Brodyanski et al., 1994),
- energy storage (Rosen, 2012), including thermochemical and thermal energy storage (Dincer and Rosen, 2010; Rosen et al., 2004), and
- transportation, including aerospace (Rosen and Etele, 2004) and automotive (Cownden et al., 2001).

To appreciate the insights brought forward with exergy methods, some applications of exergy are described further. Nduagu et al. (2012a, 2012b) use exergy and other methods to examine the sequestration of CO_2 from a coal power plant using magnesium silicate rock. A life cycle assessment of the process reveals that with heat recovery mineralizing 1 tonne of CO_2 requires 3.4-3.6 GJ, depending on the process used (Nduagu et al., 2012b). Two oil extraction methods (solvent and mechanical) from Jatropha curcas seeds are compared exergetically by Ofori-Boateng et al. (2012), demonstrating that the exergy efficiencies are 79% and 96% respectively for solvent and mechanical extraction processes. The exergy efficiency and losses of the Turkish cement production sector and its CO_2 emissions are investigated by Ziya Söğüt (2012).

The incorporation of exergy into engineering design has also received increasing attention (Bejan et al., 1996; Gaggioli, 1983).

Applications of exergy-based economic methods have been reported in a wide range of fields including electrical generation (Arsalis et al., 2009; Borgert and Velasquez, 2004; Kazim, 2005; Kwak et al., 2003; Zhang et al., 2006, 2007), cogeneration and trigeneration (Aras and Balli, 2008; Balli et al., 2008; Colpan and Yesin, 2006; Dogan and Yesin, 2005; Ozgur Colpan and Yesin, 2006; Lian et al., 2010; Silveira and Tuna, 2003, 2004; Sugimoto et al., 2006), heating (Ozturk et al., 2006; Ucar and Inalli, 2008), cooling (Jassim and Khir, 2004; Kan et al., 2010; Khir et al., 2007; Palacios Bereche et al., 2009; Sahoo et al., 2004), fuel production (Clausen et al., 2010; Rivero et al., 2004), heat exchangers (Jin et al., 2010; Zun-long et al., 2008), buildings (Arslan and Kose, 2006; Ucar, 2010), industrial systems (Fani et al., 2010; Nafey et al., 2006; Peerapong and Limmeechokchai, 2009), and hybrid systems (Ansari et al., 2010; Rensonnet et al., 2007; Uche et al., 2006).

Table 12.1. Thermophysical data for storage, charging and recovery fluids in the TES illustration

Fluid	Mass (Mg)	Temperature range (°C)	
		Low	High
Storage	5700	45	46
Charging	570	80	90
Recovery	570	15	25

Table 12.2. Energy and exergy flows, losses and efficiencies for the TES illustration

Quantity	Charged (MJ)	Recovered (MJ)	Loss (MJ)	Efficiency (%)
Energy	23,940	23,940	0	100
Exergy	4,879	399	4,480	8.2

12.2. BROADER SYSTEMS

Exergy methods have been applied to larger systems like countries and sectors of their economies. For example, analyses have been carried out for regions and countries in:

- North America, including Canada (Rosen, 1992) and the United States (Reistad, 1975; Ayres et al., 2003),
- Europe, including the United Kingdom (Hammond and Stapleton, 2001), Sweden (Wall, 1997), Italy (Wall et al., 1994) and Turkey (Ozdogan and Arikol, 1995; Rosen and Dincer, 1997b),
- the Middle East, including Saudi Arabia (Dincer et al., 2003), and
- Asia, including Japan (Wall, 1990) and China (Ji and Chen, 2006).

12.3. ILLUSTRATIONS

Several illustrations are presented here of applications of exergy that are simple, yet useful for highlighting the differences between energy and exergy methods.

12.3.1. Thermal Energy Storage

The evaluation of a thermal energy storage (TES) requires a measure of performance that is rational, meaningful and practical. TES systems receive and hold thermal energy for subsequent use, come in many types (e.g., tanks, aquifers, ponds, caverns), and can store energy at temperatures above or below the environment temperature. The conventional energy storage efficiency is an inadequate measure. A more perceptive basis for comparison is needed if the true usefulness of a thermal storage is to be assessed, and so permit maximization of its economic benefit. Efficiencies based on ratios of exergy do provide rational measures of performance, since they can measure the approach of the performance of a system to the ideal.

We use an illustration to demonstrate that the energy efficiency is an inappropriate measure of thermal storage performance. The illustration considers the seasonal TES used for a central solar heating plant in Munich, built in 2007 as part of the Solarthermie 2000 Plus program (Bauer et al., 2010). The TES is integrated with flat plate solar collectors having a surface area of 2700 m^2. The TES uses hot water as the storage medium and has a storage volume of 5700 m^3 (which holds about 5.7×10^6 kg of water).

We do not assess the operation of the Munich TES but rather, for simplicity, consider its operation under a hypothetical set of conditions. The TES is taken to be full of water and initially to be at 45°C. We also assume the TES to be perfectly insulated, and the ambient temperature to be 15°C.

A quantity of 23.9×10^6 kJ of heat is transferred to the storage through a heat exchanger from an external body of 570,000 kg of water cooling from 90°C to 80°C. This heat addition raises the storage temperature 1.0°C, to 46°C. After a period of storage, the same amount of heat (23.9×10^6 kJ) is recovered from the storage through a heat exchanger which delivers it to an external body of 570,000 kg of water, raising the temperature of that water from 15°C to 25°C. The storage is returned to its initial state at 45°C. The data for the operation of the storage are summarized in Tables 12.1 and 12.2.

For this storage cycle the energy efficiency, the ratio of the heat recovered from the storage to the heat injected, is seen in Table 12.2 to be 100%. But the recovered heat is at only 25°C, and of little use, having been degraded even though the storage energy efficiency was 100%. The exergy recovered in this example is evaluated as 399 MJ, and the exergy supplied as 4879 MJ. Thus the exergy efficiency, the ratio of the thermal exergy recovered from storage to that injected, is 8.2%, a much more meaningful expression of the achieved performance of the TES. Consequently, a device that appears to be ideal on an energy basis is correctly shown to be far from ideal on an exergy basis, clearly demonstrating the benefits of using exergy analysis in TES evaluation.

12.3.2. Electrical Heating

Electrical heating of domestic hot water and electrical space heating are considered in this illustration, using an electrical resistance heater and a heat pump. The water heater converts electricity to heat at a temperature suitable for domestic hot water. Similarly, space heater converts electricity to heat at a temperature suitable for keeping a room at a comfortable temperature.

The energy efficiency of electric resistance heating is very high, and a typical value of 99.5% is considered here. The coefficient of performance of an electric heat pump for heating, which is a measure of its energy efficiency, is dependent on the temperatures of the product heating and the surroundings. A typical value of 3 is considered here, for both domestic hot water and space heating.

In this illustration, we consider a typical small multi-unit residential building. We examine a time when the domestic hot water heater provides a thermal energy rate of 10 kW to maintain the domestic hot water at 55ºC, and the space heater provides the same heat supply rate to maintain the building temperature at 22ºC. The reference-environment temperature during the heating operations is taken to be 5ºC.

Energy and exergy rates for the product heat and input electricity are listed in Table 12.3 for the domestic hot water and space heating operations, for the electrical resistance heater and the heat pump. Also listed are energy and exergy efficiencies.

Although the energy efficiency of electric resistance heating for domestic hot water and for space heat is very high at 99.5%, implying that the maximum possible energy efficiency for electric resistance heating is 100%, this understanding is erroneous. An energy efficiency of 100% simply does not correspond to the most efficient heating device possible.

The reason for this confusion is that energy analysis ignores the fact that in these electrical resistance heating processes high-quality energy (electricity) is used to produce a relatively low-quality product (domestic hot water), or an even lower-quality product (warm air). Exergy analysis recognizes this difference in energy qualities, and indicates the exergy of the heat delivered by resistance heating to be 15% of the exergy entering the heater for domestic hot water heating, and to be 6% of the exergy entering the heater for space heating. Thus, the efficiency, based on exergy, of electric resistance heating is found to be about 15% for domestic hot water heating and 6% for space heating.

Note that the quality of the product thermal energy for domestic hot water heating is higher than that for space heating because of the higher temperature involved, but both are nonetheless low quality compared to the high temperatures than can potentially be attained via electrical heating.

We therefore obtain useful insights with exergy. Since thermodynamically ideal domestic hot water or space heating has an exergy efficiency of 100%, the same space heating can in theory be achieved using as little as 15% of the electricity used in conventional electric resistance domestic hot water heating, while the same space heating can in theory be achieved using as little as 6% of the electricity used in conventional electric resistance space heating.

Table 12.3. Energy and exergy quantities for domestic hot water and space heating using an electrical resistance heater and a heat pump

Quantity	Domestic hot water heating		Space heating	
	Electrical resistance	Heat pump	Electrical resistance	Heat pump
Product heat				
Temperature (ºC)	55	55	22	22
Energy rate (W)	10,000	10,000	10,000	10,000
Exergy rate (W)	1524	1524	576	576
Input electricity				
Energy rate (W)	10,050	3,330	10,050	3,330
Exergy rate (W)	10,050	3,330	10,050	3,330
Efficiency				
Energy (%)	99.5	300*	99.5	300*
Exergy (%)	15.2	45.8	5.7	17.3

* The energy efficiency of 300% corresponds to a value of the coefficient of performance for the heat pump with COP = 3. The energy efficiency exceeds 100% since more product heat is delivered than the electrical energy input.

The fact that the exergy efficiencies are meaningful and energy efficiencies are misleading can be seen by examining the values in Table 12.3 for domestic hot water heating and for space heating using an electric heat pump. For a heat pump with a COP of 3, domestic hot water heating and space heating are both seen to be achieved using only 33% of the electricity that electric resistance heating would require. Correspondingly, the exergy efficiencies for the heat pumps are much higher than those for electrical resistance heating (46% for domestic hot water heating and 17% for space heating).

12.3.3. Combustion

In this example, we consider the adiabatic combustion of a coal. The example is based on the coal-fired power plant examined in Chapter 20, and data are drawn from that chapter.

Before combustion, we have a system containing fuel and air at ambient conditions, which is the reference-environment temperature and pressure.

After combustion, when the fuel and air react, the system contains hot combustion gases. The temperature of the hot combustion gases depends on how much air is input to the combustion process with the fuel, and the extent of the chemical reaction.

The energy and exergy flow rates associated with the input fuel and air, and with the product combustion gases, are shown in Table 12.4. We consider three hypothetical cases for the combustion gases:

- The combustion gases are at the adiabatic flame temperature (1674ºC here), which is the highest temperature achievable for the given reactants.
- The combustion gases are at the stack gas temperature (119ºC here).
- The combustion gases are at the condenser operating temperature (36ºC here).

Note that the second case does not represent the stack gas, but rather represents the hypothetical condition in which all of the combustion gases are at the stack gas temperature. Similarly, the third case represents the hypothetical condition in which all of the combustion gases are at the condenser temperature.

Table 12.4. Changes in energy and exergy flow rates during adiabatic combustion of coal with air

Combustion stage	Quantity	Temperature (ºC)	Flow rate (MW)*	
			Energy	Exergy
Pre-combustion	Fuel and air**	15 (ambient)	1368	1427
Post-combustion	Combustion gases	1674 (adiabatic flame temperature)	1368	983
		119 (stack gas temperature)	1368	363
		36 (condenser temperature)	1368	93

* Values of energy and exergy flow rate for the first two rows are from Table 20.2b.

** The energy and exergy flow rates of fuel and air are entirely associated with the fuel; the values for air flows are zero since air is taken from the environment at the reference-environment conditions.

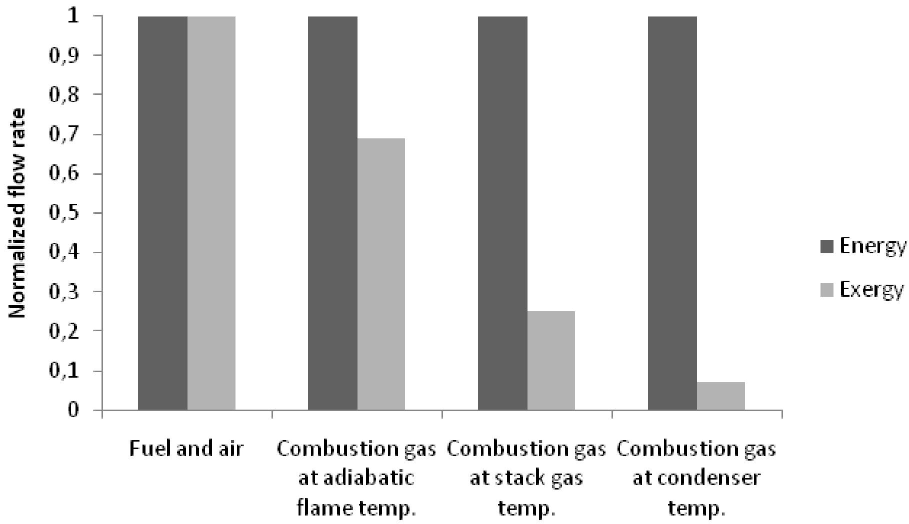

Figure 12.1. Comparison of normalized energy and exergy flows during adiabatic combustion of coal with air.

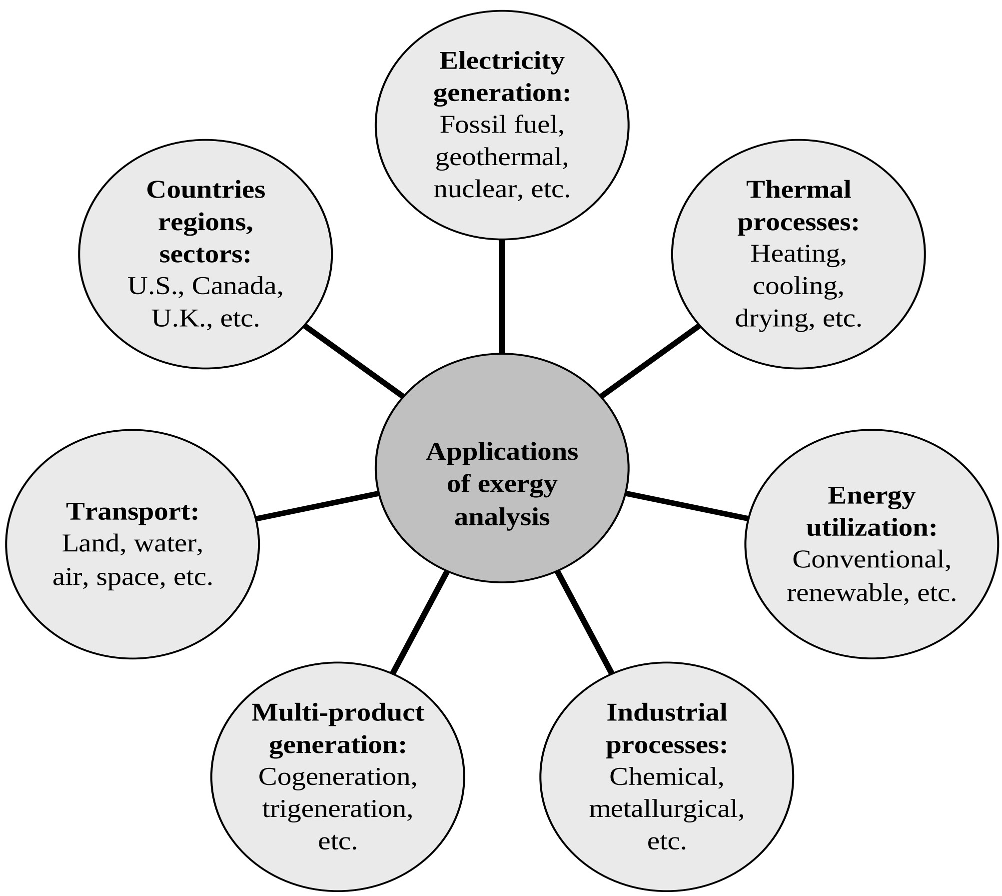

Figure 12.2. Examples of applications of exergy analysis.

It is seen in Table 12.4 that, during adiabatic combustion, the energy in the system remains fixed because it is adiabatic, regardless of the temperature of the combustion gases. But the exergy content declines as temperature of the combustion gases, and the quality of the product energy is correspondingly reduced, due to the irreversibilities associated with the conversion of the high-quality energy of fuel to the lower quality energy of combustion gases.

The behaviors of energy and exergy during adiabatic combustion are illustratively contrasted in Figure 12.1. There, normalized energy and exergy flow rates are presented for the pre- and post-combustion conditions described above. Energy flow rates are normalized by dividing by the energy flow rate of the fuel and air, while exergy flow rates are similarly normalized by dividing by the exergy flow rate of the fuel and air.

12.4. CLOSING REMARKS

Numerous applications of exergy analysis to improve efficiencies of processes and systems have been reported, ranging in size from simple to complex processes. These applications of exergy have been wide ranging, from technology improvements to national and global assessments. The applications areas include power generation, cogeneration, trigeneration, heating, refrigeration, chemical processing, fuel production, separation, distillation, desalination, energy storage, and others. Many of the considered applications involve industrial operations and economic sectors such as transportation. A summary of the numerous applications of exergy analysis to devices, systems and processes in different sectors is presented in Figure 12.2.

Chapter 13

EXERGY AND ENVIRONMENT APPLICATIONS

OVERVIEW

Applications are described of methods integrating exergy and the environment for a broad range of devices, systems and processes, as well as hybrid and integrated systems. The applications considered include heating and cooling, air conditioning, power generation and cogeneration, chemical, fuel and pulp and paper processing, transportation, and energy storage. Also considered are renewable energy sources like solar and biomass energy and renewable energy conversion technologies like hydrogen fuel cells. Categorizations of the applications are also presented. The applications highlight the benefits of the methods.

Applications of methods integrating exergy and the environment to many devices, systems and processes are reported in a wide range of fields, including heating, cooling, air conditioning, power generation, cogeneration, chemical processing, fuel production, pulp and paper processing, transportation, and energy storage. Conventional and renewable energy resources have been considered. Some areas of applications of exergy-based environmental methods are shown in Figure 13.1. In some ways, the listings in this figure are similar to the examples of exergy applications in Figure 12.2, suggesting that exergy-based environmental methods are often applicable wherever exergy analysis is applicable.

Several examples of applications reported in the literature are described in this chapter. Categorizations of the applications are also discussed.

13.1. HEATING, COOLING AND AIR CONDITIONING

Exergy-based assessments including environmental factors are reported for a variety of thermal processes related to heating and cooling, including psychrometric devices, heat pumps, drying systems and cryogenic devices (Dincer and Rosen, 2007).

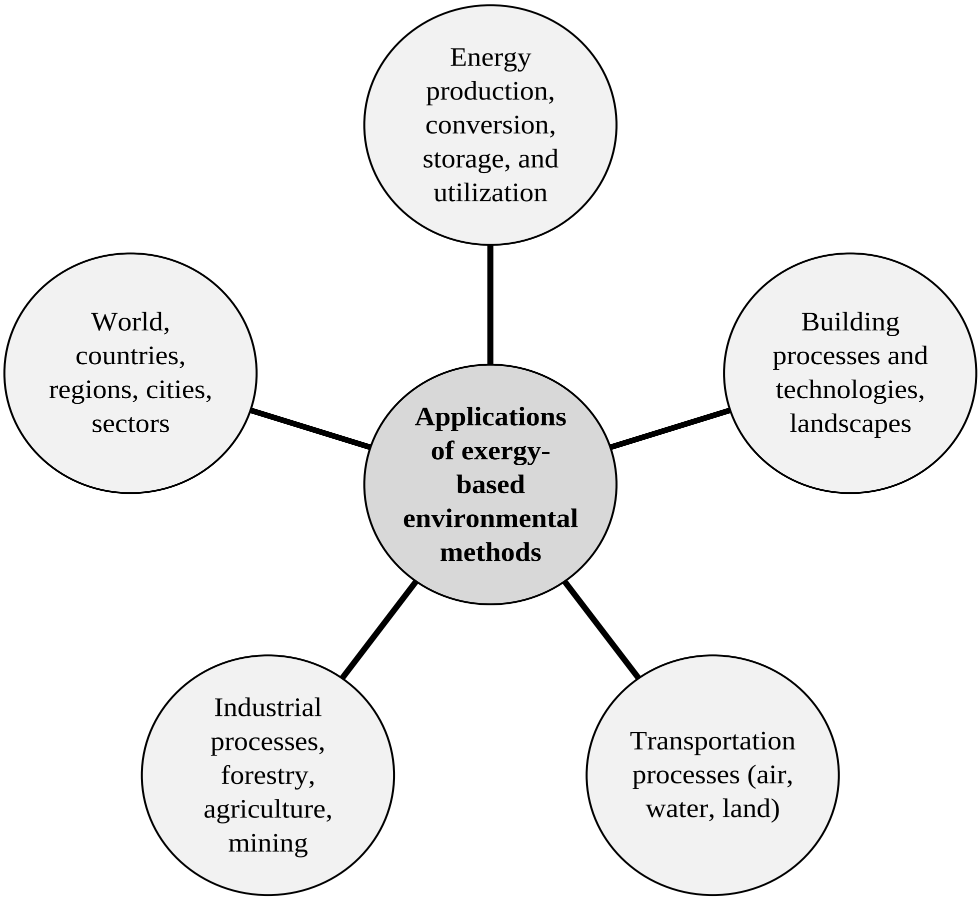

Figure 13.1. Selected examples of applications of exergy-based environmental methods.

13.1.1. Heating

EXCEM analysis is applied to a range of thermal systems and processes by Rosen and Dincer (2003c). Assessments are also carried out of ground-source heat pump systems for building applications (Ozgener et al., 2005b) and of geothermal district heating systems (Ozgener et al., 2007a).

As pointed out earlier, a district energy (district heating and cooling) system integrated with cogeneration is examined using exergy-based efficiency analysis while considering environmental benefits (Rosen et al., 2005).

A greenhouse heating system using a solar-assisted ground-source heat pump is assessed using EXCEM analysis and by investigating the relation between capital costs and thermodynamic losses for devices (Ozgener and Hepbasli, 2005). The ratios of thermodynamic loss rate to capital cost demonstrate that devices in successful air conditioning are configured so as to achieve an overall optimmum by appropriately balancing the exergy-based and economic characteristics of the overall system and its devices.

A multi-objective thermoeconomic optimization using an artificial intelligence technique known as an evolutionary algorithm is reported for a vertical ground source heat pump

(Sayyaadi et al., 2009). The assessment seeks to minimize the total levelized cost of the system product or the exergy destruction of the system. The multi-objective optimization considers thermodynamic and thermoeconomic objectives simultaneously.

13.1.2. Cooling and Air Conditioning

Jassim et al. (2005a, 2005b) thermoeconomically optimize the geometry of a precooling air reheater for air conditioning. The total cost function is optimized based on the optimum heat transfer area and total irreversibilities. A similar assessment is reported of a cold thermal energy storage system using a glycol working fluid (Bakan et al., 2008).

The scope-oriented thermoeconomic method of Piacentino and Cardona (2010a) is applied to the cost accounting of an industrial vapor-compression chiller having a cooling capacity of 1.5 MW. The role of the condenser and the throttling valve is viewed as the low isentropic efficiency limiting case for an expander. Marginal cost analyses are performed on component attributes like condensation pressure and expander isentropic efficiency to identify rational cost allocations. Design optimization of the chiller using the scope-oriented thermoeconomic method is also described by Piacentino and Cardona (2010b).

The optimal performance of two stage refrigeration systems based on a thermo-ecological performance criterion is examined by Kalaiselvam et al. (2009), providing a general tool for the ecological design of two stage refrigerators. To maximize the ecological performance function, various system parameters are varied.

13.2. Electricity Generation

Numerous exergy-based environmental investigations have been undertaken for electrical power generation. These have considered gas turbines, hydroelectric stations, solar plants, biomass plants, thermoelectric plants, fuel cells and hybrid and combined power plants.

13.2.1. Gas Turbine Power Plants

A gas turbine combined cycle is assessed with ExLCA by Lombardi (2001). The major irreversibilities are observed to be concentrated in the operating phase of the power system, and the recommendations yield an 85% reduction in CO_2 emissions via chemical absorption with a blended solution of amines.

A complex Brayton cycle for power generation is investigated considering ecological and economic conditions by Tyagi et al. (2007), who defines the ecological function as the ratio of power output to entropy generation rate and the economic function as the ratio of power output to total cost. The cycle is optimized by adjusting several operating conditions, including cycle temperatures and reheat and intercooling pressure ratios. Values are determined of turbine outlet temperature and pressure ratios at which the cycle is maximized in terms of the ecological and economic objectives while minimizing entropy generation rate.

A multi-objective design optimization is performed for a gas turbine power plant, considering exergy, economic and environmental factors (Barzegar Avval et al., 2011). The three objective functions in the optimization are

- the gas turbine exergy efficiency,
- the total cost rate of the system production (including the cost rate of environmental impact), and
- carbon dioxide emissions.

The thermoenvironomic objective function is minimized while the power plant exergy efficiency is maximized using a genetic algorithm.

13.2.2. Micro Gas Turbine Power Plants

The optimization of a micro gas turbine using exergy and economics, as well as environmental factors, is described by Mozafari et al. (2010). They consider exergy fuel costs and external social costs of air pollution, and find that optimized values for some system parameters can be affected by the inclusion or exclusion of these externalities.

13.2.3. Hydroelectric Power Plants

Hydroelectric power generation processes are analyzed by Tonon et al. (2006) with a comprehensive method based on exergetic and economic parameters, and environmental emissions. Corresponding environmental performance indicators are developed.

13.2.4. Solar and Wind Power Plants

The environmental impact of wind and solar energy processes is evaluated and compared with that for fossil fuels using ExLCA for hydrogen production (Granovskii et al., 2007). GHG and air pollution emissions are evaluated for all process steps, and renewable energy-based hydrogen production is identified as an good option for environmental improvement.

A solar-driven heat engine is investigated with thermoeconomics by Barranco-Jiménez et al. (2009), and the optimum operation conditions determined. Additionally, two design parameters are investigated subject to three objective functions:

- the power output per unit total cost,
- the efficient power per unit total cost, and
- the ecological function per unit total cost.

The ways in which technical and economical parameters affect the thermoeconomic performance are discussed for the three performance criteria.

An exergoeconomic evaluation including environmental factors of a solar thermal power plant has also been reported (Kaushik et al., 2001), while Santarelli and Macagno (2004) analyzed thermoeconomically of a photovoltaic-hydrogen system for residential buildings.

13.2.5. Biomass Power Plants

The production of biodiesel from used cooking oil is assessed with ExLCA by Peiro et al. (2010). ExLCA accounts for exergy input, complementing the environmental impacts identified with LCA. It is observed that uranium and natural gas are the main exergy inputs and that 68% of the environmental impact is associated with the transesterification process.

To evaluate objectively a new biomass conversion process for electricity generation, involving a combination of allothermal biomass gasification and a high-temperature solid oxide fuel cell, Meyer et al. (2009b) apply exergoenvironmental and exergoeconomic analyses and identify the most relevant system components from economic and environmental perspectives and potential design improvements.

13.2.6. Thermoelectric Power Plants

Thermoelectric power generation processes are analyzed by Tonon et al. (2006) with a comprehensive method based on exergetic and economic parameters, and environmental emissions. The method was also applied to hydroelectric power generation, as noted earlier.

13.2.7. Hybrid and Combined Power Plants

The performance of an innovative high-efficiency power plant – a steam power plant fed by hydrogen from coal gasification with no carbon dioxide emissions – is examined by Carrado et al. (2006) using traditional LCA and extended exergy analysis. CO_2 capture is achieved with a standard humid-CaO absorbing process. EEA considers the exergy contents of the fabrication materials and the exergy flows used during fabrication, the monetary cost of equipment on an equivalent exergy content basis, the labor contribution in terms of equivalent exergy input, and the exergy cost to bring the effluents to a state of equilibrium with the surroundings. The system exergy efficiency, accounting for external costs, decreases from 42% to 17% when CO_2 capture and sequestration is added.

Modeling and optimization of the synthesis, design and operation of advanced combined power cycles, with thermoeconomic and environomic methods, are described (Pelster et al., 2001). Also, the carbon exergy tax proposed by Borchiellini et al. (2000) is applied to a large (700 MW capacity) integrated plant that combusts two fossil fuels in distinct plants:

- a coal-fired combined plant that burns coal in a pressurized fluidized bed combustor, and
- a typical natural gas fired combined plant.

A charge on the carbon dioxide emissions is evaluated based on the analysis.

A combined power plant consisting of a solid oxide fuel cell and gas turbine is assessed using a thermoeconomic method based on a carbon exergy tax directed at increasing the efficient use of exergy resources (Santarelli, 2004). Also, as noted earlier, a hybrid system integrating solar photovoltaics and hydrogen production for residential buildings is investigated by Santarelli and Macagno (2004).

13.2.8. Comparative Assessments

The environmental sustainability indicators of Dewulf and Van Langenhove (2005), which integrate industrial ecology principles and the second law of thermodynamics, are applied to electricity production from resources that are non-renewable (natural gas and fossil oil) and renewable (hydropower, photovoltaic conversion of solar irradiation).

Oil-fired thermal and photovoltaic electricity generation are compared using emergy synthesis and LCA by Brown et al. (2012), so as to provide indicators of efficiency and environmental performance to facilitate progress toward more sustainable development.

13.3. Cogeneration, Trigeneration and Multi-Product Generation

Numerous exergy-based environmental investigations are undertaken for processes that produce multiple products simultaneously, including the cogeneration of electricity and heat.

Methods for extending exergy accounting and thermoeconomics with environmental factors are applied to a cogeneration system based on a gas turbine, yielding an optimal design (Sciubba, 2001a, 2003). An exergoeconomic-based optimization of a complex cogeneration plant is reported by Vieira et al. (2006).

Costs for a zero-emission process generating hydrogen and electricity are estimated with exergoeconomic techniques (Tsatsaronis et al., 2008).

An exergy-based efficiency analysis of a cogeneration and district energy system, with environmental benefits, is reported by Rosen et al. (2005).

Exergoeconomic estimates are presented for a zero-emission process for the generation of hydrogen and electricity (Tsatsaronis et al., 2008).

13.4. Chemical Processes, Fuel Production and Waste Treatment

Processes for chemical and fuel processing and separation vary widely. To improve designs, some of these are investigated with exergy-based environmental methods. For example, an analysis method based on exergetic, economic, environmental and other parameters isapplied to bioethanol production by Tonon et al. (2006). Also, an exergetic evaluation of the renewability of a biofuel is carried out by Berthiaume et al. (2001).

Various applications of ExLCA are reported, including some related to chemical and material processes and waste treatment:

- *Building materials*. Beccali et al. (2003) apply ExLCA to plaster materials and observe that determining the overall destroyed exergy provides a measure of resource depletion and the most suitable criterion to reduce the exergy losses and improve the efficiency of the production system. They also point out that including economics renders the methodology more useful.
- *Separation techniques*. Chemical and pharmaceutical industry separation techniques are assessed with ExLCA by Van der Vorst et al. (2009). The separation techniques are evaluated and compared in terms of their integral resource consumption and, on that basis, preparative high performance liquid chromatography is determined to be the most sustainable process.
- *Waste gas treatment*. Exergy and life cycle analyses are compared by Dewulf et al. (2001) for assessing the sustainability of waste gas treatment options (biofiltration, catalytic and thermal oxidation and active carbon adsorption). Biofiltration is identified to be the most efficient on an exergy basis.

Various hydrogen production and storage systems are examined with ExLCA by Neelis et al. (2004) for automotive applications. The results demonstrate that vehicles with a compressed hydrogen storage system have the highest exergy efficiency and that ExLCA helps quantify the resource depletion in fuel chains. Boyano et al. (2011) examine hydrogen production by steam reforming of natural gas using exergy and economic assessments combined with LCA, and identify the components with the highest environmental impacts and possible improvements.

An exergetic environmental assessment of life cycle emissions for various automobiles and fuels, which focused on emissions, is reported by Daniel and Rosen (2002). Also, the exergy of the emissions for two energy conversion technologies, considering their potentials for environmental impact, are compared and contrasted (Crane et al., 1992).

More generally, the use of exergoeconomic methodologies for the analysis and optimization of process operations and systems is reported by Zhang et al. (2000).

The integration of electrolysis into synthetic natural gas production from wood is investigated by applying a multi-objective optimization algorithm with a thermoeconomic process model for the thermochemical process (Gassner and Maréchal, 2008). The electrolyzer provides

- an efficient and economic option for ensuring sufficient hydrogen is present for complete conversion of wood to methane, thereby increasing the output of synthetic natural gas, and
- a potential by-product in the form of oxygen.

The process yields a product, which is essentially CO_2 free and which can be used in transportation and other applications, from renewable energy resources.

Biomass gasification energy conversion systems have been assessed and optimized with thermoeconomic methods by Brown et al. (2009). They consider a wood gasification, gas cleaning and energy conversion process of moderate size (i.e., a thermal energy input rate via wood of 20 MW), and focus on electricity generation costs and avoidance of tar formation to prevent equipment fouling. The optimization involves multiple objectives, and quantifies the trade-off between total investment costs and the exergy efficiency of electricity production. The systems assessed incorporate fluidized bed gasifiers with three alternative inputs (air, oxygen, steam) as well as two alternative electricity generation systems (an internal combustion engine combined cycle requiring cold gas cleaning, a gas turbine combined cycle requiring hot gas cleaning). It is determined that low-pressure and high-temperature operating conditions maximize the efficiency of the internal combustion engine combined cycle with cold gas cleaning and simultaneously favor minimal tar formation. Tar concentrations are observed to be higher for the gas turbine combined cycle (but this may not be problematic since hot gas cleaning can prevent tar condensation).

Life cycle assessment and exergetic life cycle assessment are applied to biodiesel production from used cooking oil in Spain (Peiro et al., 2010). It is demonstrated that transesterification is responsible for about 70% of the total environmental impact, and that the environmental impacts can be reduced by up to 36% if targets set by the Spain's renewable energy plan are achieved.

Various other industrial processes are examined with exergy-based environmental methods. The environmental impact of ceramics are evaluated using exergy analysis (Kita et al., 2010), and a set of environmental sustainability indicators integrating industrial ecology principles with the second law of thermodynamics are applied to petrochemical- and oleochemical-based production of alcohols and to end-of-life options for polyethylene (Dewulf and Van Langenhove, 2005). Exergy-based evaluations of environmental impact are carried out for the production of ammonium nitrate and nitric acid (Kirova-Yordanova, 2010, 2011). In that work, the following exergy-based indicators are used for comparing the efficiency and environmental impact of treatment processes: reduction of the exergy of the emissions from the overall process, exergy of additional emissions from the treatment process, net reduction of the exergy consumption, and Cumulative Energy Consumption (CEnC) and Cumulative Exergy Consumption (CExC) of natural resources as a result of the waste flows treatment. Diaz-Mendez et al. (2012) apply extended exergy accounting to flaring in oil fields, in order to quantify the environmental externality linked to the chemicals released by an elevated flare stack (SO_x and NO_x). The results provide the exergy release to the environment by the stack and its cost in primary resource equivalents, and show that these parameters can be reduced with hot gas recycling.

13.5. Agriculture and Pulp and Paper Processes

An agricultural production is evaluated by Hoang and Prasada Rao (2010) using a cumulative exergy balance approach. The authors contend that the use of cumulative exergy content overcomes problems with conventional methods, by including life cycle assessment and facilitating the analysis of the cumulative pollution and effects on natural resources.

A pulp and paper mill with cogeneration is optimized using an integration of three optimization methods that incorporate environmental factors (Cortés and Rivera, 2010): exergoeconomics, thermoeconomics and pinch analysis. The results lead to higher efficiencies and lower operational costs compared to the results when the different optimization methods are utilized in isolation. The integrated methodology determines optimal operating conditions and identifies components having the highest irreversibilities, and suggest several plant modifications:

- Alterations of the operations for the recovery boiler, the turbogenerator, the thermal treatment unit and the deaerator.
- The addition of a line of evaporators, to offset the higher irreversibilities in the existing evaporator line.
- The addition of heat transformers for heat recycling so as to reduce the emission of waste heat to the atmosphere.

13.6. TRANSPORTATION

Exergy and environmental analyses, some including economic factors, are reported of various transportation systems, including:

- automobiles (Crane et al., 1992; Daniel and Rosen, 2002; Granovskii et al., 2006a, 2006b), including a vehicular PEM fuel cell system (Mert et al., 2007).
- aircraft (Etele and Rosen, 1999, 2001; Rosen and Etele, 2004; Rosen, 2009). An exergy-based economic analysis is reported of the global performance of a typical turbofan engine and its components, considering the entire flight cycle and flight phases and identifying internal and exhaust flow costs (Tona et al., 2010). Exergy-based economic methods are identified by those authors as particularly useful for cost reduction and configuration optimization in the aeronautical industry, due to its incorporation of extremely complex aircraft designs and highly integrated systems.

Broader comparative assessments are also reported. Ji et al. (2009), for instance, carry out an exergy-based assessment of waste gas emissions for the transportation sector (road, rail, water and civil aviation) for China from 1978 to 2004. They quantify the environmental impact per unit of traffic service via an index of emission exergy intensity, defined as the ratio of the total chemical exergy of the emissions to the total converted turnover of the transportation vehicles.

13.7. ENERGY STORAGE

Exergy-based assessments including environmental factors are reported for a variety of energy storage processes (Rosen, 2012), including thermal storage technologies, e.g., see chapter 6 of Dincer and Rosen (2010).

13.8. BUILDINGS AND LANDSCAPES

Energy and material needs for a residence, in terms of construction and use, are quantified with ExLCA by De Meester et al. (2009). It is found that heating requirements during usage account for the main resource input (accounting for 60% of the total annual exergy consumption) for efficient buildings, and that non-renewable inputs are dominant for construction (accounting for 62% of total exergy extracted from the environment for the wooden frame building type, and 85-86% for the cavity wall and external insulation type).

Liu et al. (2010) describe a generic exergy-based assessment for the environmental impact of the building life cycle in Chongqing, China, focusing on the natural environment. For environmental impacts, the authors consider energy consumption, resource consumption and pollutant discharge via energy-embodied exergy, resource chemical exergy and abatement exergy, respectively. It is determined that energy use accounts for about 75% of the total environmental impact during a 50-year building life cycle, and that 80% of that value is associated with the operation phase and 15% with the building material production phase.

Exergy analysis with LCA is applied for building envelope efficiency retrofits in the city of Ningbo China (Zhou and Gong, 2011). It is determined that the cumulative saved energy consumption in the use stage equals the embodied energy of the newly added insulation materials in the product stage after 15 years.

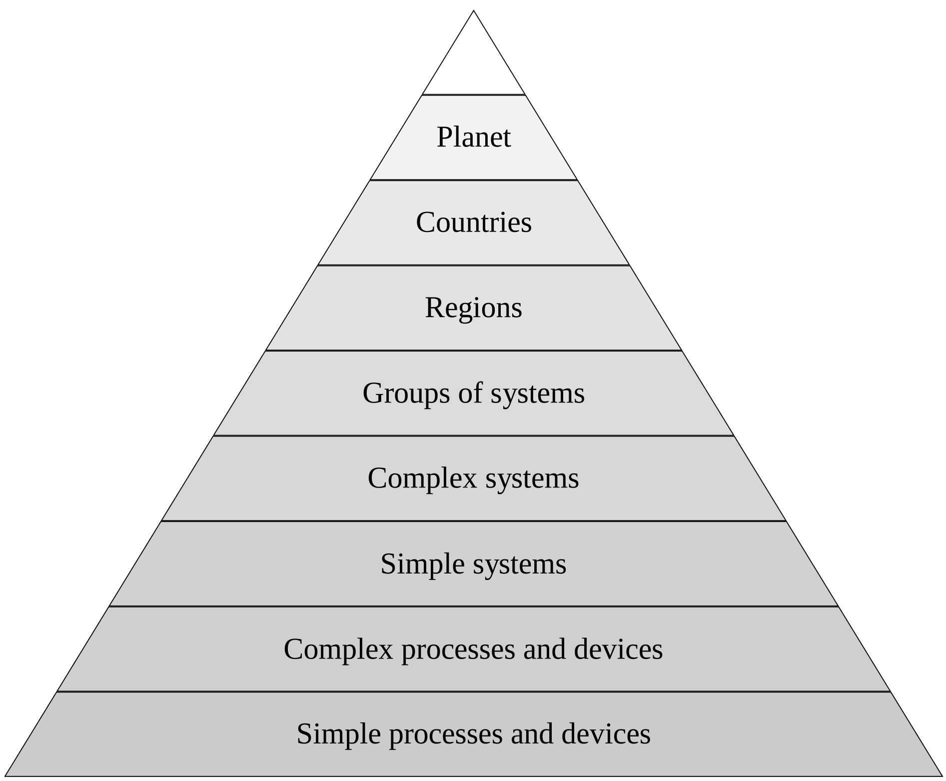

Figure 13.2. Categorization of types of applications of methods integrating exergy and the environment based on scale and complexity.

The disciplines of building engineering, architecture, urban planning and landscape design have recently begun using the second law of thermodynamics and exergy to reduce energy consumption in the built environment. For instance, Stremke et al. (2011) explore the application of the second law and exergy in sustainable landscape design, and propose several exergy-conscious design principles.

13.9. Categorizations of Applications

The applications of methods integrating exergy and the environment can be categorized in various ways that emphasize different features of the applications and are instructive for readers. Two such categorizations are presented here.

The applications of methods integrating exergy and the environment can roughly organized in a hierarchical manner, based on scale and complexity. This is illustrated in Figure 13.2, where the types of applications of methods integrating exergy and the environment are shown in such a breakdown. The applications range from the simple and basic at the foundation to large systems like countries and the planet at the apex. Complex systems include multi-product systems.

Applications of methods integrating exergy and the environment can also be divided by sector. Such a categorization is shown in Figure 13.3 for many applications considered here.

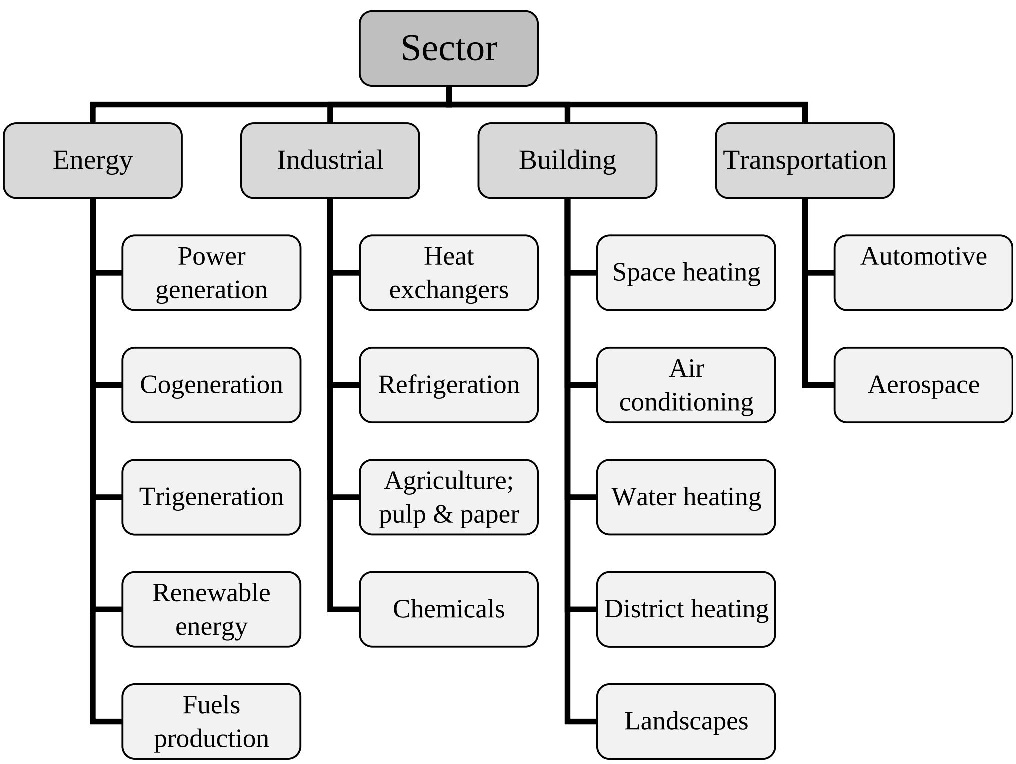

Figure 13.3. Devices and processes, broken down by sector, for which methods integrating exergy and the environment are applied.

13.10. Closing Remarks

Various applications of methods integrating exergy and the environment are presented for many devices, systems and processes. The applications considered represent a wide range of fields, including heating, cooling, air conditioning, power generation, cogeneration, trigeneration, chemical processing, fuel production, pulp and paper processing, transportation, and energy storage. Several renewable energy sources and conversion technologies are considered, such as solar thermal and photovoltaic devices, hydraulic and biomass systems, and hydrogen and fuel cell systems. Also considered are industrial operations and hybrid systems. Categorizations of the applications are also presented.

Chapter 14

EXERGY AND ECOLOGY APPLICATIONS

OVERVIEW

Various applications of exergy-based ecological indicators are described. These demonstrate the use of these indicators in detecting and evaluating environmental responses to pollution, mitigation or avoiding the harmful impacts of different uses and effective ecosystem management. Numerous ecosystems are examined, including aquatic ecosystems (lakes, lagoons, seas) and biological communities. The stresses in ecosystems due to the changes caused by pollution make it important to have meaningful indicators for assessing the effects of pollution in those communities.

Exergy-based indicators of integrity are applicable to various ecosystems, and provide useful aids, facilitating detection of environmental responses to pollution, evaluation of the responses, mitigation or avoidance of the harmful impacts of different uses and effective ecosystem management.

Exergy-based ecological models and methods have been applied to various ecosystems, including many aquatic and land-based ones, as well as ecological communities. A particularly large area of interest has been aquatic ecosystems, for which many exergy-based indicators of ecosystem integrity exist. The stresses in aquatic environments due to the changes caused by pollution render it important to have meaningful indicators for assessing the effects of pollution in those communities.

14.1. LAKES

Lake ecosystems are investigated from may perspectives using exergy-based methods.

14.1.1. Development and Evolution

The application of exergy in the ecological modeling of a lake environment is reviewed by Zhang and Wang (1998), demonstrating that exergy can be used as a goal function for parameters in ecological models for lakes and reservoirs, as an ecological indicator for the development and evolution of lake ecosystems, and as a component of structural dynamic models that account for changes in ecosystems.

Ludovisi and Poletti (1999) apply exergy and structural exergy as ecological indicators for the development state of homogeneous lake ecosystems.

14.1.2. Species and Health

The exergetic responses to changes in phytoplankton growth parameters and species composition are examined for a generic lake by Salomonsen and Jensen (1996). In that work, exergy is used as a measure of the build-up of biological structure of a natural lake ecosystem, and the maximum utilization of system resources as represented by the maximum exergy build-up is examined. The results support exergy as an object function in lake models.

Xu (1997) apply exergy-based ecological indicators (exergy and structural exergy) to assess the development state of the ecosystem of Lake Chao, a eutrophic in China. Also, the restoration of riparian wetlands and macrophytes in Lake Chao is assessed. Modeling reveals that macrophyte restoration can decrease phytoplaniton biomass, increase fish biomass, exergy, structural exergy, zooplankton/phytoplankton ratio and transparency, leading to the conclusion that macrophyte restoration can purify lake water, regulate lake biological structure and control eutrophication (Xu et al., 1999).

An aquatic ecosystem consisting of the mesocosms and microcosms of Lake Baikal is assessed by examining the behavior of exergy and structural exergy (Silow and Oh, 2004). The structural exergy of the communities decreases after the addition of allochtonous compounds (peptone, diesel oil, *o*-biphenyl, $CdCl_2$) to the mesocosms and after the addition of toxicants to the microcosms. Furthermore, a significant decrease of structural exergy in the polluted area is observed when comparing the exergy contents for benthos in regions affected by discharges from Baikalsk Pulp and Paper and unaffected regions, supporting the use of structural exergy as a measure of ecosystem health. Furthermore, the application of exergy in ecological modeling and natural ecosystem monitoring is examined for aquatic ecosystem studies, particularly the lake Baikal ecosystem, by Silow and Mokry (2010).

14.1.3. Structural Changes

Using exergy and structural exergy as ecological indicators, system-level responses of experimental lake ecosystems are determined by Xu et al. (2002) for three chemical stresses:

- acidification,
- copper, and
- pesticide contamination.

The doses and toxicity of the chemical stressors contribute to changes in exergy and structural exergy. Large changes occur sometimes, indicating the ecosystems are seriously contaminated by the chemical stressors, while small changes are observed at other times (e.g., when low doses were used), suggesting the lake ecosystems are not significantly impacted by those chemical stressors. The observed changes in exergy and structural exergy are consistent with expectations of reduced food chains, resource-use efficiency, stability, information and exergy in stressed aquatic ecosystems. Exergy and structural exergy are concluded to be feasible ecological indicators of system-level responses of lake ecosystems to chemical stress.

14.1.4. Food Chains

Exergy methods are applied to the pelagic trophic food chain in Lago Maggiore, Switzerland for 1978-1992, partly by determining the exergy content in the food chain (de Bernardi and Jorgensen, 1998). The approach is useful for verifying ecological models, describing mechanisms in the food chain function, estimating the food chain efficiency in utilizing available resources, and predicting the most important ecosystem function factors.

14.2. Lagoons

The exergy index and specific exergy are both applied as ecological indicators of organically enriched regions in the Mar Menor lagoon, a Mediterranean coastal lagoon in south-eastern Spain (Salas et al., 2005). The exergy index and specific exergy provided useful information on community structure. But these indicators did not distinguish levels of organic enrichment or the effects of all types of pollution, leading the authors to comment that exergy and specific exergy are not sufficient alone to act as comprehensive ecological indicators.

14.3. Seas and Beaches

Exergy is applied as an ecosystem indicator during the recovery of marine benthic communities, considering benthic communities in the sandy and muddy bottoms of the North Adriatic Sea (Libralato et al., 2006). The complex dynamics in a disturbed community during recovery processes are usually difficult to assess with conventional indices, but exergy as a measure of the departure of a system from equilibrium is proposed as a useful ecological indicator in this context. A controlled trawl fishing haul is the disturbance. The local exergy storage of the benthic community is used and exergy is estimated with data for

- trophic groups,
- coding genes for broad taxonomical groups, and
- genome size.

Local exergy content decreases in disturbed areas, peaking in the sandy and muddy bottom one month after the disturbance and subsequently increasing to the reference or surrounding level. This result is consistent with the dynamics of exergy storage during the development of systems. As anticipated, the dynamics of exergy in the two habitats differ.

Exergy is consequently cited as a useful indicator, in that it integrates the underlying recovery processes of benthic communities after disturbances.

The sandy beaches along the Ligurian coast in the north-west Mediterranean Sea are analyzed with thermodynamic and network analyses by Vassallo et al. (2012).

14.4. BIOLOGICAL SYSTEMS

The results for the recovery of marine benthic communities in the North Adriatic Sea, from the previous section, may be extendable to biological systems (Libralato et al., 2006).

14.5. MACROINVERTEBRATE COMMUNITIES AND PLANTS

Park et al. (2006) use self-organizing maps to pattern the exergy of benthic macroinvertebrate communities. With data for 650 sites in the Netherlands including 855 species, the exergy is calculated using biomass data for five trophic functional groups:

- carnivores
- detritivores
- detritivore–herbivores
- herbivores
- omnivores

The response of the exergy of the different trophic groups varies with ecosystem characteristics. Patterning changes of exergy is concluded to be an effective technique for evaluating ecosystems, and exergy is viewed as an effective ecological indicator.

Reis and Miguel (2006) report an exergy balance of green leaves, which examines not only the health development of the ecosystem, but also potential disruptions.

Emergy and eco-exergy methods are used in China to evaluate four forest restoration modes (Lu et al., 2011): acacia mangium plantation, mixed-native species plantation, conifer plantation and eucalyptus plantation. In addition, the eco-exergies of the four forest restoration modes are evaluated, and combined with emergy to explore the restoration and self-organization efficiencies of these modes. The joint use of eco-exergy and emergy analysis is found to be useful for comparing different or similar of ecosystems.

The application of chemical exergy as a unified and objective indicator for assessing and optimizing land treatment systems is explored by Tzanakakis and Angelakis (2011), using data from a field trial for four plant species. All species receive partially treated domestic wastewater based on their water requirements. Chemical exergy is observed to provide a unified, holistic and objective assessment of the effluent quality and the changes in the properties of soil, and understanding of the efficiency with which plant species use wastewater is obtained via the chemical exergy use efficiency.

14.6. REVIEWS

Applications of eco-exergy for the assessment of ecosystem health and development of structurally dynamic models are reviewed by Zhang et al. (2010) and limitations and possible future applications of the approach are examined.

Numerous applications of theoretical aspects of systems ecology are described in a new book by Jorgensen (2012).

14.7. CLOSING REMARKS

Many applications of exergy-based ecological indicators of various types are reported. Many of these demonstrate the use of such indicators for a range of useful purposes, such as:

- detecting environmental responses to pollution,
- evaluating environmental responses to pollution,
- mitigation or avoiding the harmful impacts of different responses, and
- effective ecosystem management.

Various ecosystems have been examined, including aquatic ecosystems like lakes, lagoons and seas, and several biological communities. The stresses in ecosystems due to the changes caused by pollution make it important to have meaningful indicators for assessing the effects of pollution in those communities.

Chapter 15

ASSESSING EARTH'S RESOURCES USING EXERGY

OVERVIEW

An exergy-based perspective is provided of resources and their use on Earth and in its primary constituencies: the biosphere, people and civilization's energy system. These constituencies consume exergy, but not energy. This alternative viewpoint helps elucidate the environmental impact associated with resource use and degradation and enhances understanding of how people, civilizations and nature operate and interconnect.

In this section, we provide a perspective, from the viewpoint of exergy, on resources on Earth and their use in its major energy-transaction constituencies:

- the biosphere (which consists of all living organisms),
- people, and
- civilization's energy system (including all anthropogenic systems).

15.1. RATIONALE

Exergy flows and consumptions are compared for the Earth, so as to develop a good understanding of the resources available on Earth, as well as the exergy utilized by natural and anthropogenic energy systems. Natural energy systems are those of the environment and of ecosystems. This information helps understand how people, civilizations and nature operate, and the relations between them.

Table 15.1. Exergy consumption rates for the Earth and selected constituencies

Constituency	Exergy consumption rate (TW)
Earth	178,000
Biosphere of Earth	100
Energy systems of civilization on Earth	13.3
People on Earth	0.79

15.2. Approach and Data

This section is based on an earlier investigation (Rosen and Scott, 2003), and follows the approach used therein.

Data for the year 2000 (EIA, 2001) are used, although for natural energy flows through the environment data from older sources (Hafele, 1981; WEC, 1995) are used and assumed representative of 2000. In the earlier work:

- The exergy consumption for Earth is approximated as the difference between (a) the exergy delivered to Earth via solar radiation and planetary motion or extracted from sources of exergy in the Earth (geothermal, fossil fuels, uranium), and (b) the waste exergy emitted by the Earth. The latter term is assumed to be the exergy of long-wave radiation emitted from Earth to space, which, because it is taken to be emitted at the Earth's environment temperature, is zero.
- The exergy destruction of the biosphere is taken to be the difference between (a) the exergy input to plant life via photosynthesis, and (b) the exergy of the waste heat to which the input exergy is eventually dissipated (whether the plant matter dies and decomposes or is eaten first).
- The exergy consumption for people is taken to be the difference between the exergy they consume via food and the exergy of waste materials and heat emitted. For simplicity, we evaluate exergy consumption for people based on metabolic rates, which vary depending on such factors as body size and level of physical activity.
- The exergy consumption for civilization's energy system is taken to be the difference between the exergy input and the waste exergy output.
- Although Earth's mean surface temperature is 288 K, a mean "biosphere" surface temperature of 293 K is used since the biosphere, people and civilization's energy system are predominantly located in warmer regions of the Earth.

15.3. Exergy Consumptions and Resource Use

The exergy consumptions for Earth and its main constituencies are presented in Table 15.1 and discussed in the following sections.

15.3.1. Earth

The exergy input via each of solar radiation and planetary motion is approximated as equal to the energy input. The energy input rate via solar radiation, 178,000 TW (Hafele, 1981), greatly exceeds other energy inputs (e.g., the energy from tides and geothermal sources are about 40 TW (Hafele, 1981; WEC, 1995)), so the exergy consumption of Earth is equal to the exergy input via solar radiation. The exergy/energy ratio for solar radiation is approximated as 0.95 (i.e., 1 – 288 K/5800 K), where the temperature of the sun is 5800 K. Thus, the exergy rate of the radiation incident on the Earth and the exergy consumption rate of Earth are both 169,000 TW.

15.3.2. Earth's Biosphere

All input energy is in the form of solar radiation, which drives the process of photosynthesis and produces carbohydrates. Waste heat is assumed emitted at the biosphere's temperature. Material wastes are taken to have no exergy after they finish decomposing, and the exergy input is taken to be the energy input multiplied by the exergy/energy ratio cited earlier of 0.95. The energy input rate is 100 TW (Hafele, 1981), and the exergy consumption rate and exergy input rate for the biosphere are thus 95 TW.

15.3.3. People

The World Health Organization (WHO, 1985) evaluates the energy requirements of people based on metabolic rates, and the results are used to estimate energy requirements for different categories of people. The daily energy consumption of the average person is approximately 2690 kcal (WHO, 1985). The per-person value is multiplied by Earth's population for the year 2000 (approximately 6.1 billion) to obtain the total values. The exergy consumption rate for people is therefore determined to be 0.79 TW.

15.3.4. Civilization's Energy System

The exergy of all waste output is considered zero as, for simplicity, waste energy output is taken to be heat at the reference-environment temperature (although some wastes contain exergy.) The exergy input is approximated as the same as the energy input, which is reasonable since the exergy-to-energy ratio for most energy forms considered is near unity. Material wastes like combustion products that are emitted to the environment by civilization's energy system are assumed to degrade to equilibrium with the environment over sufficiently long time frames. The energy input to civilization's energy system is 14.0 TW (11.2 TW fossil fuels, 1.0 TW uranium, 1.4 TW biomass, 0.4 TW hydraulic, 0.01 TW geothermal, and 0.05 TW other sources like solar, wind and tidal).

15.4. ANALYSIS AND COMPARISON

15.4.1. Interpretation

The exergy consumption rate of civilization's energy system (14.0 TW) is more than four orders of magnitude less than that for Earth, and one order of magnitude less than that for Earth's biosphere, but one order of magnitude greater than that for people.

The sun provides the Earth with a high-exergy input (relative to the Earth's exergy needs), which the Earth degrades—through natural processes or via the provision of energy services—and emits as low-exergy thermal radiation. The biosphere utilizes exergy from solar radiation to create high-exergy products. People consume exergy via food and thus are able to do work and provide services and to retain the molecular organization of their bodies.

15.4.2. Environmental and Ecological Implications

The results in this chapter have important implications regarding environmental impact and ecology. The environmental impact attributable to Earth's biosphere is now likely much greater than that attributable to civilization's energy system, since the biosphere consumes so much more exergy. But, if civilization's energy use increases several fold, its environmental impact could approach that of the biosphere.

15.4.3. Future Implications

The exergy consumption of the Earth's biosphere is approximately ten times larger than civilization's energy system, but that could change with growth in population and per capita energy use. Today, Earth's exergy consumption is almost entirely due to natural processes, but in the future, civilization's energy system could come to have an exergy consumption approaching that of life itself. That is, if the entire population of Earth consumes exergy at the same per capita rate and with the same efficiencies as occurs in industrialized countries at present, then the exergy consumption by civilization's energy system could approach the same order of magnitude as Earth's biosphere.

Today, exergy consumption and entropy production on Earth are almost entirely due to natural processes. In the future, civilization's energy system could come to have an environmental impact approaching that of life itself. This could easily be true in terms of exergy consumption. However, the biosphere's impact on Earth's climate is mainly associated with how living systems are changing Earth's atmosphere. The major impact of civilization's energy system thus may relate to how its emissions will change the atmosphere.

15.5. Closing Remarks

An exergy-based perspective is provided of resources on Earth and the manner in which they are used in the main energy-transaction constituencies: the biosphere, people and civilization's energy system. It is demonstrated that the Earth and its biosphere, people and energy system do not consume energy, but do consume exergy. This perspective can enhance understanding of how people, civilizations and nature operate and interconnect, and provide an alternate view of the environmental impact associated with resource use and degradation.

Chapter 16

ASSESSING POLLUTED MATERIALS

OVERVIEW

An exergy viewpoint is provided into the assessment of wastes and polluted materials. Although not a measure of impacts like toxicity, exergy can help assess the impact of pollution in a natural body and determine the minimal work needed to restore the environment to its original state. The minimal work used to separate a pollutant from a liquid mixture is determined, and explained in terms of its applicability for assessing the dispersion of contaminants in the atmosphere, hydrosphere and lithosphere.

Wastes, in solid or liquid or gaseous form, are usually generated during processes. Some of the wastes are recycled and some are released to the environment, often after treatment. Recycling and treatment processes can be analyzed with exergy methods.

Assessing the impact of waste disposal to the environment is complex and done in various ways. Many methods are empirical, e.g., determining a contaminant's toxicity and the ability of the environment to receive it. Usually these methods do not utilize exergy since it does not provide a measure of toxicity.

Some exergy-based methods exist to assess the impact of the disposal of waste in the environment. Two examples follow:

- Some suggest that the impact of pollution in a natural body like a river can be quantified using an exergy-based parameter variable. For instance, the manner by which the exergy (mechanical, thermal, chemical) of a river is affected by the presence of contaminants is assessed by Zaleta-Aguilar et al. (1998).
- The impact of pollution can also be assessed by determining the minimal work needed to restore the environment to its state before the contamination. This minimal work is the exergy of the contaminated flow relative to the clean one. The restoration process depends on the type of pollution and can involve various processes, e.g., chemical reaction, separation, heating, cooling, compression and expansion. For example, the minimal work can be determined to concentrate CO_2 from atmospheric concentration (about 390 ppm in 2011) to 100% CO_2 gas.

Regarding the latter bullet, the net exergy consumption (CNEx) provides an approximation of the minimum work needed to return a system (a resource and its environment) to its initial state, for high-exergy substances like fossil fuels. For a contaminant with low exergy content, the minimal work needed to extract the compound from the environment can be considered when there is no treatment facility. This approach is applicable regardless of toxicity, even though thermodynamics does not address toxicology.

We now consider the minimal work used to separate a pollutant from a liquid mixture. The same approach likely can be used for the dispersion of contaminants in the atmosphere and in the lithosphere.

16.1. Separation of a Pollutant from a Liquid Mixture

Exergy can be used to evaluate the minimal work used to separate a pollutant from a liquid mixture. Henley and Seader (1981) express the minimal work ($-W_{min}$) required for the separation of liquid mixtures at low pressure as follows:

$$-W_{\mathrm{min}} = RT_{\mathrm{o}}\left\{\sum_{out} n_{\mathrm{k}}\left[\sum_{i} x_{\mathrm{i,k}} \ln \gamma_{\mathrm{i,k}} x_{\mathrm{i,k}}\right] - \sum_{in} n_{\mathrm{j}}\left[\sum_{i} x_{\mathrm{i,j}} \ln \gamma_{\mathrm{i,j}} x_{\mathrm{i,j}}\right]\right\} \tag{16.1}$$

where both inlet and outlet liquid streams are taken to be at the environment temperature. Here, n denotes number of moles, x mole fraction, γ activity coefficient, T_o environment temperature and R the universal gas constant (8.314 kJ/kmol K). Subscripts i, j and k denote stream components, entering streams and exiting streams, respectively.

If there are only two components (a contaminant in a liquid) and all solutions are ideal (i.e., $\gamma = 1$), the work (or exergy) of restoration W_R from Equation (16.1) becomes

$$-W_{\mathrm{R}} = RT_{\mathrm{o}}\left(n_2 x_{\mathrm{C,2}} \ln x_{\mathrm{C,2}} - n_1 x_{\mathrm{C,1}} \ln x_{\mathrm{C,1}}\right) \tag{16.2}$$

where subscripts 1 and 2 denote respectively the polluted stream and the extracted contaminant stream, while $x_{C,2}$ and $x_{C,1}$ denote respectively the contaminant mole fractions of the cleaned and polluted flows. If the extracted contaminant is pure, $x_{C,2} = 1$.

Equation (16.2) applies if we consider the dispersion of a contaminant in the hydrosphere (e.g., pesticide dispersion in a lake), which can be modeled as water polluted with a contaminant. The mixture is to be separated into clean water and contaminant, and the inlet and outlet streams are at the same pressure and temperature. The following approximation for the molar fraction of the contaminant $x_{C,1}$ is reasonable for low concentrations:

$$x \cong C \frac{M_{\mathrm{H2O}}}{M_{\mathrm{C}}\rho} \tag{16.3}$$

Here, C denotes the contaminant concentration and ρ the density of water, while M_{H2O} and M_C denote the molecular weight of water (18 kg/kmol) and the contaminant, respectively.

16.2. ILLUSTRATIVE EXAMPLE

Considering a body of water of 1500 m^3 at T_o = 293 K contaminated with the pesticide atrazine at a concentration of 5 μg/l, the minimum work of restoration needed to extract the atrazine is determined. Given the molecular weight M is 216 kg/kmol for atrazine and 18 kg/kmol for water, the molar fraction of the contaminant can be expressed with Equation (16.3) as follows:

$$x = 5 \times 10^{-6} \times \frac{18}{216} \times 10^{-3} = 4.167 \times 10^{-10}$$

Also,

$$n \cong \frac{1.5 \times 10^{6}}{18} = 8.33 \times 10^{4} \text{ kmol}$$

The work of restoration can be determined with Equation (16.2), noting that the second term in parentheses in that equation is zero if $x_{C,1} = 0$, as follows:

$$W_R = -8.31 \times 293 \times 8.33 \times 10^{4} \times 4.17 \times 10^{-10} \ln\left(4.17 \times 10^{-10}\right) = 1.8 \text{ kJ (or 0.002 MJ)}$$

The CNEx for water treatment for this case is 692 MJ and the work required as 2100 MJ, based on values evaluated in a later chapter (see Table 24.4). Therefore, there is a wide discrepancy in results between the theoretical and real values, especially if the contaminant is highly diluted as in the case of a pesticide.

16.3. INTERPRETATION

This approach for assessing the impact of water pollution suggests utilizes exergy concepts and indicates that the higher the dispersion of a given amount of contaminant, implying a larger volume of water to be treated, the greater is the work required to extract the contaminant.

As a consequence, the approach yields two main insights:

- As a contaminant becomes increasingly dispersed into a body of water, the higher is the impact since more work is required to extract a more dispersed contaminant than a concentrated one. This result appears contradictory to the fact that short-term toxicity usually decreases with a decreased concentration but it may be meaningful from the long-term toxicity perspective. That is because the exposed population increases as the dispersion of a pollutant increases.
- This result is meaningful when wastes are considered as potential usable resources, as they are harder to retrieve when dispersed in the environment.

Note that the volume of the body of water (1500 m^3) considered here is relatively small from an overall environment perspective. A wider dispersion of contaminants would involve a much larger body of water.

16.4. Closing Remarks

The assessment of wastes and polluted materials is considered from an exergy perspective, including recycling and treatment. Although exergy does not provide a measure of some environmental impacts like toxicity, exergy-based methods can help assess the impact of pollution in a natural body as well as determine the minimal work needed to restore the environment to its state before the contamination. The minimal work used to separate a pollutant from a liquid mixture is determined, and explained in terms of applicability for assessing the dispersion of contaminants in the atmosphere, hydrosphere and lithosphere.

Chapter 17

ALLOCATING CARBON DIOXIDE EMISSIONS FOR COGENERATION USING EXERGY

OVERVIEW

The allocation of emissions for an energy process that has multiple products and multiple inputs, like cogeneration, is not straightforward. Exergy methods can form the basis of rational and meaningful allocation methods for emissions, and an exergy-based method for allocating carbon dioxide emissions for cogeneration systems is described in this chapter and compared with other allocation methods. The reasoning behind an exergy-based method is discussed, as are problems associated with other methods. The exergy-based method is argued to be rational, useful and superior to other allocation methods. By permitting carbon dioxide emissions to be allocated more appropriately among cogenerated commodities, the results allow the environmental benefits of technologies that produce multiple products to be better understood and exploited.

Many companies, government agencies and researchers have struggled with the question of how to allocate emissions for an energy system that has multiple products and multiple inputs. Some work has been carried out in this area, especially for cogeneration, or combined heat and power (CHP). For example, several attempts are reported to determine how to allocate emissions among the products of cogeneration systems (Strickland and Nyboer, 2002a, 2002b; Upton, 2001; Phylipsen et al., 1998). The benefits and potential of cogeneration are discussed elsewhere (Klein, 1999a, 1999b, 1999c, 2001a, 2001b).

However, the results related to allocations obtained thus far are not universally accepted and, in the view of the author, are often not based on sound reasoning. In addition, the results obtained to date are often conflicting. Further, the methods developed often are overly complex, thus rendering it difficult to use them and to convince decision and policy makers of their potential benefits.

One clear example of the problems in this area can be seen by examining the work on CHP systems. The several existing methods of allocating emissions among outputs include “efficiency methods,” “work potential methods” and “heat content methods.” The results obtained with each method are generally different. Further, the reasoning behind each is often suspect and/or lacking. The situation illustrated by this example for CHP systems becomes even more difficult to address for more complex systems, such as those involving trigeneration (the simultaneous production of electrical, heating and cooling services).

The direct use of exergy methods can form the basis of sound and meaningful allocation methods for emissions. In this chapter, we investigate rational methods, based on exergy, for allocating emissions for complex energy systems having multiple inputs and products, like cogeneration systems. This method is compared with other allocation methods. Note that this chapter focuses on carbon dioxide for simplicity and because it is the primary greenhouse gas. But, the material is extendable to CO_2 equivalent emissions in terms of greenhouse gas potential.

17.1. COGENERATION AND EMISSIONS

Many governments have launched initiatives involving air issues and the energy sector. For instance, Environment Canada has pursued the Ozone Annex, NO_x/VOC Plan and acid rain initiatives, the Strategic Options Process for air toxics, and the National Plan for Climate Change. Environment Canada is interested in emissions trading and energy quality in the industry, and its implications for air quality issues across Canada.

Much work on defining cogeneration and assessing the performance of systems and their emissions has been carried out by European government bodies and agencies. For instance, the European Parliament (2004) issued a directive in February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market. Also, the European Committee for Standardization (CEN) and European Committee for Electrotechnical Standardization (CENELEC) published in 2004 a workshop agreement manual for determination of combined heat and power (CEN/CENELEC, 2004). Although these two documents have been criticized (Verbruggen, 2007a, 2007b), they are widely accepted for primary energy savings for cogeneration. They provide indicators for carbon dioxide emissions allocation from cogeneration systems. However, these documents ignore exergy, and thus suffer from the same difficulties as mentioned earlier of allocation methods.

With a move towards output-based standards for emission guidelines, emissions trading, and comparative evaluations of air pollution and greenhouse gases (GHGs) for all energy sources, better information is needed on the equivalence between heat, cooling and electricity. Both shaft mechanical power and electricity are more valuable than most forms of industrial heat, but this depends on the temperature and quality of the steam or hot water cogenerated. The normal definition of efficiency (fuel utilization) does not capture this relationship.

The concept of comparing emission mass per unit energy output (in kg/MWh, for example) of various emissions must consider the trade-off between electricity and heat for cogeneration and district energy, if suitable comparisons are to be made. This has been done in an approximate fashion for the 1992 Canadian Council of Ministers of the Environment (CCME) Gas Turbine emission guideline. More definitive work is needed to address this issue for energy products such as high- and low-pressure steam, and hot and cold water. Such estimations can also be valuable for the conversion of emission factors from kg/MWh, into $/tonne externalities and $/MWh of reduction measures.

Emissions trading for air pollution and GHGs will require a shared allocation of credits/allowances among several industrial and commercial energy producers and users.

17.2. COGENERATION AND RELATED ENERGY SYSTEMS

Cogeneration usually refers to the simultaneous production of two energy forms (electricity, and heat in the form of steam and/or hot water) from one energy source (normally a fossil fuel). Cogeneration has been used, particularly by industry, for approximately a century. A cogenerator can be a utility, an industry, a government, or any other party.

Cogeneration systems are often extensions of thermal electricity-generation systems. In thermal electrical generating stations, the energy content of a resource (normally a fossil fuel) is converted to heat (in the form of steam or hot gases) which is then converted to mechanical energy (in the form of a rotating shaft), which in turn is converted to electricity. A portion (normally 20 to 45%) of the heat is converted to electricity, and the remainder is rejected to the environment as waste.

Cogeneration systems are similar to thermal electricity-generation systems, except that a percentage of the generated heat is delivered as a product, normally as steam or hot water, and the quantities of electricity and waste heat produced are reduced. Overall cogeneration efficiencies based on both the electrical and thermal energy products of over 80% are achievable. Other advantages generally reported from cogenerating thermal and electrical energy rather than generating the same products in separate processes include:

- reduced energy consumption,
- reduced environmental emissions (due to reduced energy consumption and the use of modern technologies in large, central installations), and
- more economic, safe and reliable operation.

Most thermal systems for large-scale electricity generation are based on steam and/or gas turbine cycles, and can be modified relatively straightforwardly for cogeneration.

Two main categories of heat demands can normally be satisfied through cogeneration:

- residential, commercial and institutional processes, which require large quantities of heat at relatively low temperatures (e.g., for air and water heating); and
- industrial processes, which require heat at a wide range of temperatures (e.g., for drying, heating and boiling in, for instance, chemical processing, manufacturing, metal processing, mining and agriculture).

The use of a central heat supply to meet residential, commercial and institutional heat demands is often referred to as district heating. As well as satisfying heat demands, cogenerated heat can drive chillers; this application can be particularly beneficial in locations where the annual peak electrical demand is associated with the summer cooling load.

Many general descriptions and studies of cogeneration systems have been reported (MacRae, 1992; Rogner, 1993; FVB/Eltec, 1993; MacLaren, 1988; Henneforth and Todd, 1988; Acres, 1987; Horlock, 1987; Rosen, 1993, 1994, 1998; Rosen et al., 1997; Hart and Rosen, 1994; Rosen and Le, 1994, 1996; Sherwood and Rosen, 1996; Simpson and Rosen, 1996). Cogeneration systems are in use throughout the world (e.g., over 4000 are listed by the Association of Energy Engineers), and the basic technology is proven. Numerous examples exist of large cogeneration systems:

- a steam-turbine plant in Switzerland generates 465 MW of thermal power and 135 MW of electrical power, with an overall efficiency of 75%;
- a nuclear power plant in Michigan left incomplete due to lack of funding was eventually completed as a gas-fired combined-cycle cogeneration plant having 12 heat recovery steam generators and gas turbines and two steam turbines, producing 1400 MW of electrical power and 285,000 kg/hr of steam; and
- approximately ten plants are used to generate 240 MW of electrical power and to supply 90% of the 1500 MW thermal demand for the city of Malmo, Sweden (population 250,000). Fuel drives two of the plants (an extraction steam-turbine plant generating 110 MW of electrical power and 240 MW of thermal power, and a back-pressure steam-turbine plant generating 130 MW of electrical power and 300 MW of thermal power), while the remaining plants operate on waste heat from neighboring industries (e.g., smelting, carbon-black production, sewage treatment and refuse incineration).

The size and type of a cogeneration system are normally selected to match as optimally as possible the thermal and electrical demands. Many matching schemes can be used. Systems can be designed to satisfy the electrical or thermal base-loads, or to follow the electrical or thermal loads. Storage systems for electricity (e.g., batteries) or heat (e.g., hot water or steam tanks) are often used to overcome periods when demands and supplies for either electricity or heat are not coincident. Cogeneration systems are sometimes used to supply only the peak portions of the electrical or thermal demands.

17.3. Exergy Values for Cogeneration Commodities

When allocating carbon dioxide emissions based on the exergy contents of the products in a cogeneration process, it is necessary to know the exergy values associated with electrical and thermal energy. The situation for electrical energy is straightforward, as the energy and exergy contents of electricity are equivalent. For thermal energy, however, the energy and exergy contents generally differ, and the differences in some cases can be quite significant.

Values of the energy and exergy associated with thermal energy, when it is treated purely as heat, are presented in Table 17.1 and illustrated in Figure 17.1. That table and figure consider heat (i.e., thermal energy transferred at temperatures above the environment temperature) and cold (i.e., thermal energy transferred at temperatures below the environment temperature), for various temperature categories. The ratio of exergy to energy is also shown in Table 17.1 and illustrated in Figure 17.2. Some interesting observations can be made:

- For heat, the ratio of exergy to energy varies from zero when the thermal energy is transferred at the environment temperature to unity as the temperature of heat transfer approaches infinity.
- For cold, the values of exergy rate are negative, implying that although heat is taken out of a system to make it colder, the exergy associated with the thermal energy is input to the system to make it colder. That is the flows of energy and exergy in such instances are in opposite directions. This observation implies what is intuitively

understood when dealing with systems at below-environment temperatures: cold is the useful commodity.

- Also for cold, the magnitude of the ratio of exergy to energy varies from zero when the thermal energy is transferred at the environment temperature to greater than unity as the temperature of heat transfer approaches absolute zero. For very cold systems, therefore, the exergy transfer can be larger than the energy transfer.

Thermal energy is often transferred via a medium, and in cogeneration systems the medium of choice is often water. Values of the energy and exergy of water in various forms are presented in Table 17.2. That table considers water conveying heating capacity (e.g., superheated steam, dry saturated steam, hot water), and cooling capacity (e.g., cold water). The ratio of exergy to energy is also shown in Table 17.2. Similar observations as for Table 17.1 can be made, in that the magnitudes of energy and exergy flows differ and, for cold commodities, the flows of energy and exergy are in opposite directions.

An overall qualitative comparison of the energy quality of a range of energy forms, where exergy is used as the measure of quality, is shown in Figure 17.3.

Table 17.1. Comparison of quality of various types of thermal energy, for a fixed energy rate of 1000 kW*

Thermal energy type	Temperature category**	Temperature (K)	Temperature (°C)	Exergy rate (kW)	Exergy-to-energy ratio
Heat	Low	293	20	0	0.000
		323	50	93	0.093
	Medium	373	100	215	0.215
		473	200	381	0.381
		573	300	489	0.489
	High	773	500	621	0.621
		1273	1000	770	0.770
		1773	1500	835	0.835
		2273	2000	871	0.871
Cold***	Moderate	283	10	–35	–0.035
		273	0	–73	–0.073
		263	–10	–114	–0.114
	Very low	243	–30	–206	–0.206
		223	–50	–314	–0.314
	Cryogenic	173	–100	–694	–0.694
		123	–150	–1382	–1.382
		73	–200	–3014	–3.014
		23	–250	–11,740	–11.74

* Reference-environment temperature T_o = 20°C = 293 K.
** The breakdown of temperature categories used here is arbitrary.
*** Cold is taken to be a transfer of thermal energy at below environmental temperatures.

Table 17.2. Comparison of quality of water in various conditions*

Thermal category of water	Condition of water	Temp. categ.**	Temp. (°C)	Pres. (bar)	Specific energy (kJ/kg)	Specific exergy (kJ/kg)	Ratio of exergy to energy
Hot	Superheated steam	High	700	40	3822	1677	0.439
		Medium	500	40	3361	1372	0.408
		Low	300	40	2919	1146	0.393
	Dry saturated steam	High	200	15.54	2709	912	0.337
		Medium	150	4.758	2663	747	0.281
		Low	100	1.014	2592	525	0.203
	Liquid hot water	High	100	1.014	335	39.9	0.119
		Medium	50	0.126	125	6.93	0.0553
		Low	30	0.0425	41.8	0.78	0.0187
Cold	Liquid cold water	Moderate	10	0.0123	–42	0.778	–0.0185
			5	0.00872	–63	1.524	–0.0274
			0	0.00611	–84	3.021	–0.0360

* Reference-environment temperature and pressure are T_o = 20°C = 293 K and P_o = 1 bar, respectively.
** The breakdown of temperature categories used here is arbitrary.

17.4. ALLOCATION METHODS FOR COGENERATION CO_2 EMISSIONS

Several methods have been developed for allocating carbon dioxide emissions from cogeneration to the electrical and thermal energy products. The need for these methods is premised on the fact that when the owner of a cogeneration plant, the thermal energy user and the electrical energy user are not the same, a method for allocating the emissions is needed to ensure each party is credited with their appropriate share of the emissions from the system. In addition, having a meaningful allocation method allows the sources of carbon dioxide and other emissions to be better understood and, where appropriate, reduced.

Several methods of calculating the fuel allocation to the thermal and electrical products of a cogeneration system are listed by Strickland and Nyboer (2002a, 2002b). They adapt the calculation methods introduced earlier by Phylipsen et al. (1998), in which the fuel allocation is multiplied by the appropriate carbon dioxide emission factor to evaluate the share of emissions allocated to each product.

Others have also investigated methods for allocating greenhouse gas emissions associated with manufacturing and other industries. Such investigations have been carried out by the World Resources Institute, Washington, DC and the National Council for Air and Stream Improvement, Corvallis, OR, as evidenced by correspondences between these organizations

(Upton, 2001). In general, the allocation methods discussed by Upton (2001) are variations on those discussed by Strickland and Nyboer (2002a, 2002b) and Phylipsen et al. (1998).

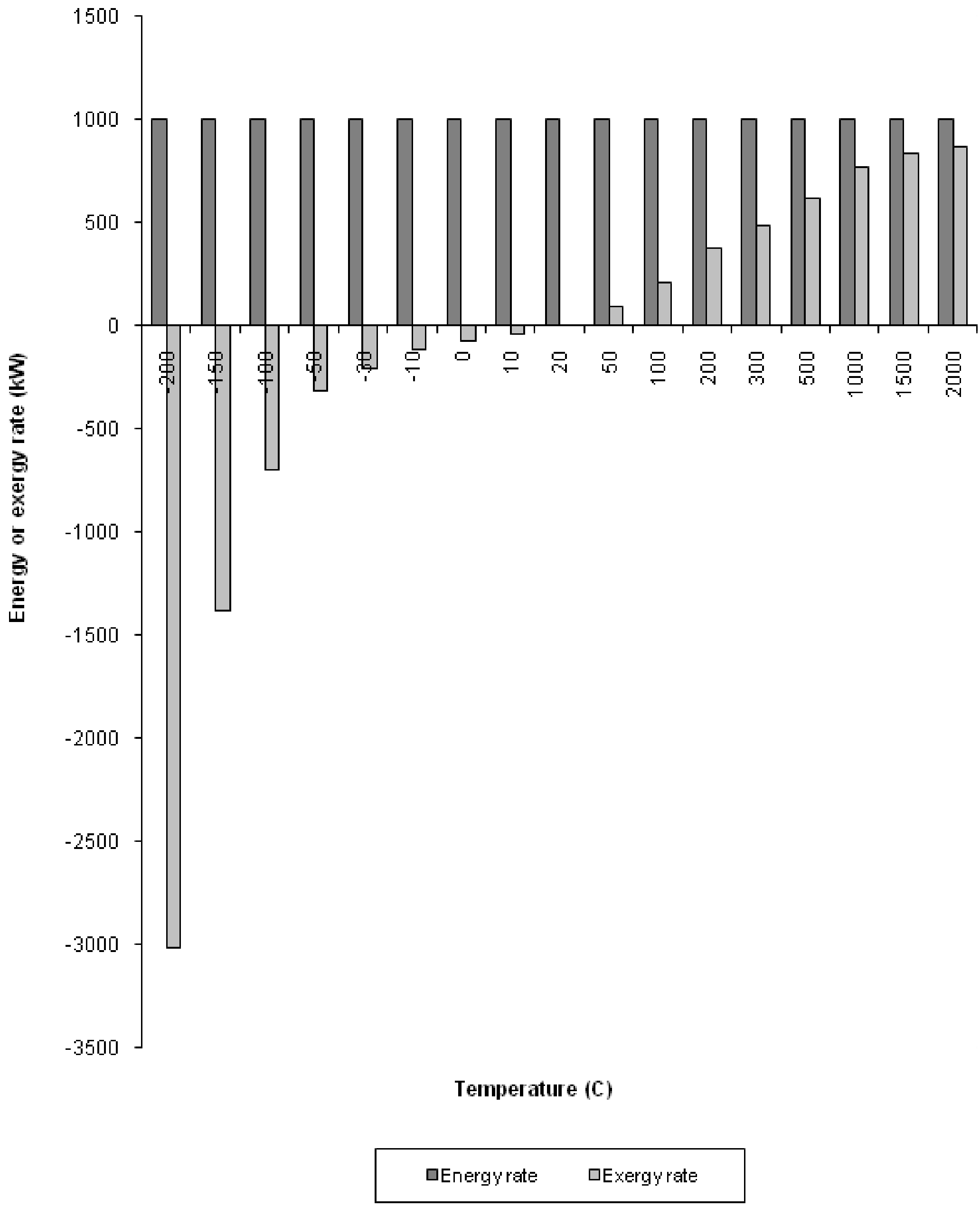

Figure 17.1. Comparison of thermal energy and thermal exergy at various temperatures (based on data in Table 17.1).

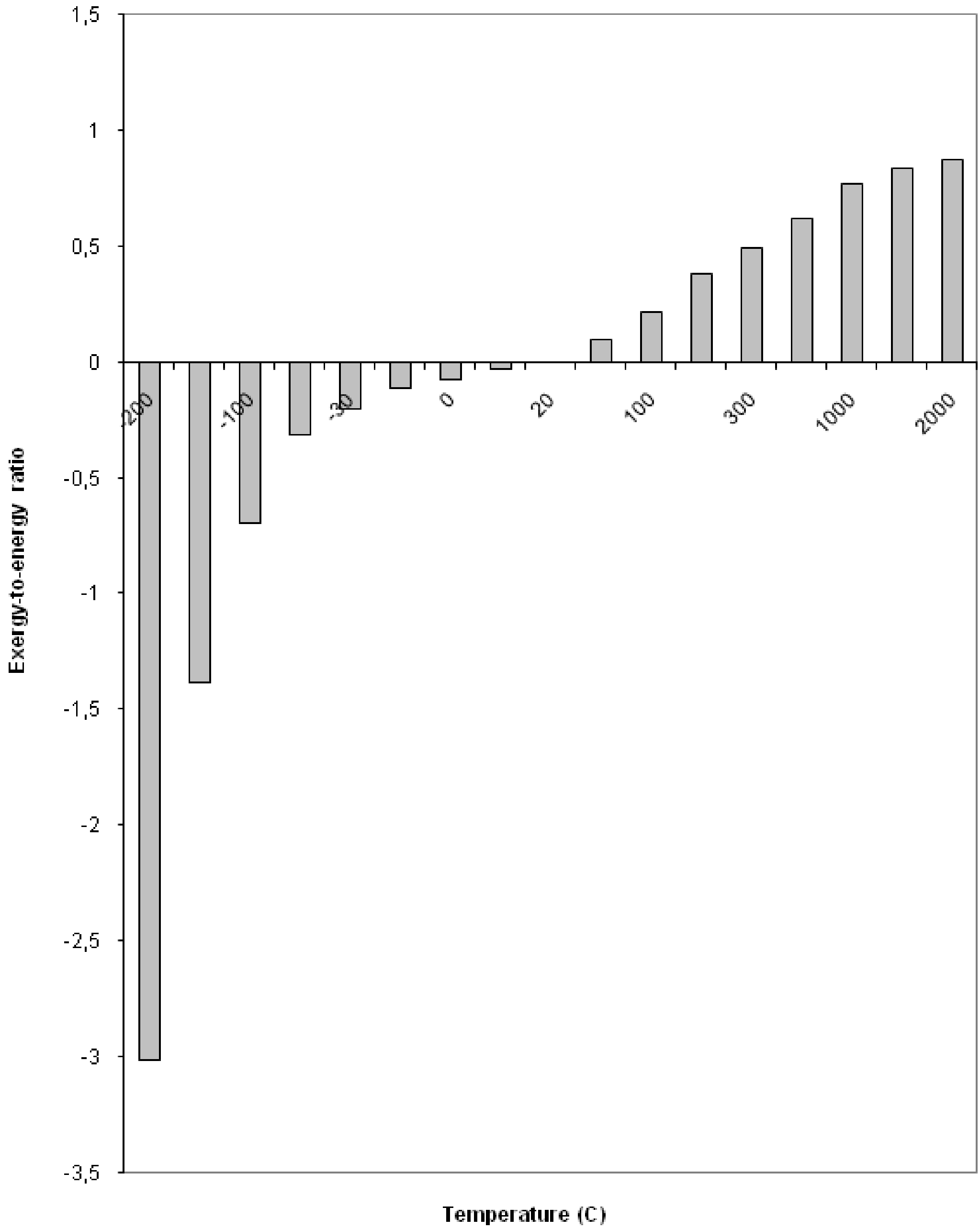

Figure 17.2. Ratio of thermal exergy to thermal energy at various temperatures (based on data in Table 17.1).

The allocation methods of Strickland and Nyboer (2002a, 2002b) and Phylipsen et al. (1998) are adapted and simplified here so that they present the *fractions*, rather than the total, carbon dioxide emissions allocated to each product. The categorizations follow for convenience those used by Strickland and Nyboer (2002a, 2002b).

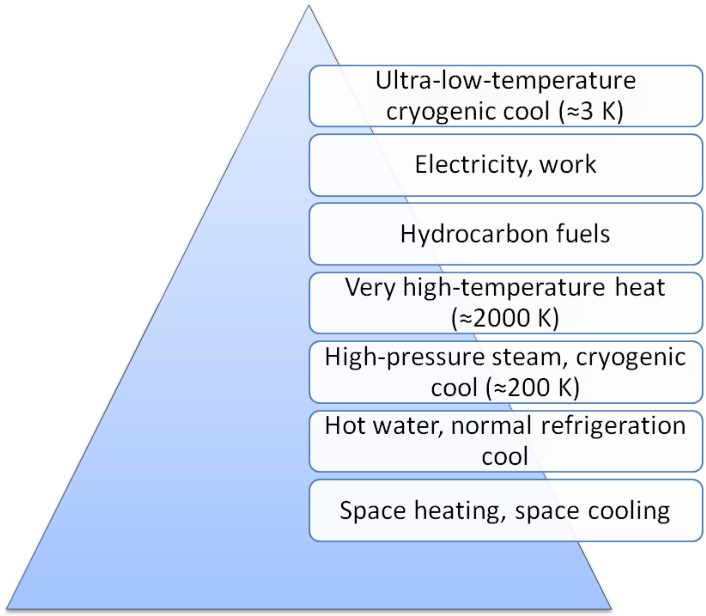

Figure 17.3. Quality of energy based on exergy for various energy forms (in descending order).

17.4.1. Allocation Based on Energy Content of Products

Allocations are evaluated in proportion to the energy contents of the products, as follows:

$$f_E = E/(E + Q) \tag{17.1}$$

$$f_Q = Q/(E + Q) \tag{17.2}$$

where f_E and f_Q denote respectively the emissions fractions allocated to the electrical and thermal products, and E and Q denote respectively the net outputs of electrical and thermal energy from cogeneration. The term Q can represent an actual transfer of thermal energy, or the net thermal energy transferred via a material flow in and out of a heat exchange device.

Although this allocation method is straightforward and simple, it ignores the quality of energy and focuses only on the quantities involved. Consequently, it can be argued that it underestimates the share of the emissions allocated to the electrical product.

17.4.2. Allocation Based on Exergy Content of Products

Allocations are evaluated in proportion to the exergy contents of the products, as follows:

$$f_E = Ex_E/(Ex_E + Ex_Q) \tag{17.3}$$

$$f_Q = Ex_Q/(Ex_E + Ex_Q) \tag{17.4}$$

where Ex_E and Ex_Q denote respectively the net outputs of electrical and thermal exergy from the cogeneration system. Note that electrical energy and exergy are equivalent, i.e., $Ex_E = E$.

In this allocation method, one can treat the thermal product in two ways: thermal energy or thermal energy transfer via moving materials. Both approaches are described below.

For simple thermal energy, the corresponding thermal exergy can be written as

$$Ex_Q = Q\tau \tag{17.5}$$

where τ denotes the exergetic temperature factor and can be evaluated as

$$\tau = 1 - T_o/T \tag{17.6}$$

here, T denotes the temperature at which heat Q crosses the system boundary, and T_o denotes the temperature of the reference environment. For a reference environment at a temperature of 300 K (27°C), the value of the exergetic temperature factor τ is 0.25 for heat transfers at 400 K, 0.5 for heat transfers at 600 K, and 0.75 for heat transfers at 1200 K.

If, on the other hand, the thermal energy is delivered via a material flow through a heat exchange device, then the term Ex_Q is evaluated as the difference between the exergy of the incoming and outgoing flows. The flowing commodity could be steam, hot water, cold water, etc., and the factors that must be taken into account in determining the corresponding exergy flow rates include mass flow rate, temperature, pressure and sometimes vapor fraction.

An additional point regarding the exergy-based allocation method is that the choice of reference environment for determining exergy quantities is important, and can affect the results. Normal practice involves selecting a reference environment that is similar to the actual environment. But other reference environments can be used. For example, Upton (2001), in an exercise to allocate emissions, evaluates exergy values using a reference-environment temperature of 100°C, which is well in excess of the actual environment annual mean temperature (perhaps 10°C to 20°C, depending on location). He uses this value because it is related to the process, in that he considers thermal energy below this temperature to be non-useful. Although this choice of a reference-environment temperature is permitted when using exergy methods, it is important to note that care must be exercised to ensure that a consistent reference environment is used throughout an analysis.

Note that the exergy-based allocation method presented by Strickland and Nyboer (2002a, 2002b) is not general, as it assumes the cogenerated thermal product can be modeled only as pure thermal energy, rather than also considering heat transfer via flowing materials.

This allocation method accounts for the quality and quantity of the commodities involved. Consequently, compared to the energy allocation method, the exergy method avoids underestimating the share of the emissions allocated to the electrical product, and allocates a lower portion of the emissions to the thermal product.

17.4.3. Allocation Based on Economic Value of Products

Allocations are evaluated in proportion to the economic values of the products as follows:

$$f_E = c_E E/(c_E E + c_Q Q) \tag{17.7}$$

$$f_Q = c_E Q/(c_E E + c_Q Q) \tag{17.8}$$

where c_E and c_Q denote respectively the unit economic values of the electrical and thermal products of cogeneration. Two important points are noted:

- The unit economic values presented here are on an energy basis (i.e., the economic value of a type of energy commodity per unit quantity of energy of that commodity), but the unit economic values can also be based on other quantities—such as exergy.
- The economic values can be determined using several economic measures in several ways. For instance, they can reflect as the costs to produce the commodities, or their prices, or some other economic measure for them.

This method is sometimes considered to have advantages to owners of cogeneration systems that sell electrical and thermal products separately.

It is not necessary to know the numerical values of both unit economic values, c_E and c_Q, when applying this method of emission allocation. Rather, it is the ratio of the unit economic values that is important. This point can be better seen by modifying the expressions for f_E and f_Q for this method of allocation as follows:

$$f_E = E/[E + Q(c_E/c_Q)^{-1}] \tag{17.9}$$

$$f_Q = Q/[E(c_E/c_Q) + Q] \tag{17.10}$$

here, c_E/c_Q denotes the ratio of the unit economic value for electricity to that for thermal energy. Since the unit economic value for electricity normally exceeds that for thermal energy, it is usually found that $c_E/c_Q > 1$.

17.4.4. Allocation Based on Incremental Fuel Consumption to Electrical Production

The emissions allocations are evaluated here by dividing the total fuel consumed in the cogeneration system among the electrical and thermal products, while considering electricity generation to be a by-product of the thermal energy production process. Then, the emissions are allocated in proportion to the fuel division.

Two steps are used to divide the fuel consumption.

First, the fuel consumption attributed to thermal energy production is evaluated as the hypothetical amount of fuel that would be consumed by an independent device for providing the same thermal energy as the cogeneration system (e.g., a reference steam boiler if the thermal energy is in the form of steam). That is,

$$F_Q = Q/\eta_b \tag{17.11}$$

where F_Q denotes the fuel consumption attributed to the production of thermal energy Q, and η_b denotes the energy efficiency of the independent device for providing the same thermal energy as the cogeneration system (e.g., a reference steam boiler).

Second, the fuel consumption attributed to electricity generation, F_E, is evaluated by subtracting this hypothetical amount of fuel from the total primary fuel energy consumed by the cogeneration system, F. That is,

$$F_E = F - F_Q \tag{17.12}$$

Then, the emission allocation fractions f_E and f_Q are determined as the ratios F_E/F and F_Q/F, respectively. That is,

$$f_Q = Q/(F\eta_b) \tag{17.13}$$

$$f_E = 1 - f_Q \tag{17.14}$$

This allocation method is consistent with the “Fuel Charged to Power” (FCP) method used by many cogeneration consulting firms.

17.4.5. Allocation Based on Incremental Fuel Consumption to Thermal Energy Production

This emissions allocation method is similar to the previous one, except emissions allocations are evaluated by dividing the total fuel consumed in cogeneration among the electrical and thermal products, while considering thermal energy production to be a by-product of the electricity generation process. Again, the emissions are then allocated in proportion to the fuel division, using the following two steps to divide the fuel consumption.

First, the fuel consumption attributed to electricity generation is evaluated as the hypothetical amount of fuel that would be consumed by an independent device for providing the same electrical energy as the cogeneration system (e.g., a reference power plant). That is,

$$F_E = E/\eta_{pp} \tag{17.15}$$

where η_{pp} denotes the energy efficiency of the independent device for providing the same electrical energy as the cogeneration system (e.g., a reference power plant).

Second, the fuel consumption attributed to thermal energy production, F_Q, is evaluated by subtracting this hypothetical amount of fuel from the total primary fuel energy consumed by the cogeneration system. That is,

$$F_Q = F - F_E \qquad 17.16)$$

Again, the emission allocation fractions f_E and f_Q are then determined as the ratios F_E/F and F_Q/F, respectively, as follows:

$$f_E = E/(F\eta_{pp}) \tag{17.17}$$

$$f_Q = 1 - f_E \tag{17.18}$$

17.4.6. Allocation Based on Shared Emission Savings between Electrical and Thermal Energy

The allocations are evaluated for each product in proportion to the hypothetical fuel that would be used to produce that product independently, relative to the total hypothetical fuel that would be used to produce both products independently.

Using the terms previously defined, the hypothetical fuel consumption attributed to an independent process for thermal energy production (e.g., a reference steam boiler if the thermal energy is in the form of steam) is evaluated as

$$F_Q = Q/\eta_b \tag{17.19}$$

and the hypothetical fuel consumption attributed to an independent process for electricity generation is evaluated as

$$F_E = E/\eta_{pp} \tag{17.20}$$

Then, the emission allocation fractions f_E and f_Q are determined as the ratios F_E/F and F_Q/F, respectively, as follows:

$$f_E = (E/\eta_{pp})/(E/\eta_{pp} + Q/\eta_b) \tag{17.21}$$

$$f_Q = (Q/\eta_b)/(E/\eta_{pp} + Q/\eta_b) \tag{17.22}$$

This allocation method therefore shares the emissions among the products in a particular format. This method somewhat extends the concepts used in the previous two emissions allocation methods, but is more of a compromise in terms of treating one or the other product as the primary one.

17.4.7. Allocation by Agreement

Allocation of CO_2 emissions to each product of cogeneration can be determined purely based on an agreement between the various parties involved in a project.

17.4.8. Allocation Based on Other Factors

Of course, emissions can be allocated according to other formulas and based on other factors.

17.5. Allocating Carbon Dioxide Emissions for Cogeneration Processes

Reasons are explained why the this author believes that most rational and meaningful method of allocating carbon dioxide emissions for cogeneration processes is based on the exergy content of products. To support this contention, the emissions allocation methods for cogeneration processes in the previous section are examined and compared. First, however, it is useful to understand the basic intentions and considerations in allocating emissions.

17.5.1. Objective in Allocating Emissions for Multi-Product Processes

The general objective when allocating a type of emission for a production process with multiple products is to allocate the emission to each product according to the actual emission that is in fact attributable to that product, accounting for all thermodynamic losses, when it is produced in the multi-product production process. Usually the emission allocation breakdown is directly proportional to the breakdown of fuel use that is attributable to each product, when it is produced in the multi-product production process.

17.5.2. Basic Considerations in Allocating CO_2 Emissions for Cogeneration

Following this description and considering carbon dioxide emissions for a cogeneration process, the total CO_2 emissions, C, for a multi-product production process can be expressed as

$$C = C_E + C_Q \tag{17.23}$$

where C_E and C_Q denote respectively the CO_2 emissions associated with the electrical and thermal energy products, when they are produced in the cogeneration process. We can also express the total CO_2 emissions as

$$C = F\varphi \tag{17.24}$$

where F denotes the total fuel use in the process and φ a CO_2 emission coefficient for the fuel. The terms F and φ must be on consistent bases (e.g., if F is in energy units, then φ must be the CO_2 emission per unit fuel energy consumed). The total CO_2 emission can also be written as

$$C = (F_E + F_Q)\varphi \tag{17.25}$$

where F_E and F_Q denote respectively the fuel consumption associated with the electrical and thermal products, when they are produced via cogeneration. Clearly, $F_E + F_Q = F$. Also,

$$C = (f_E + f_Q)F\varphi \tag{17.26}$$

where

$$f_E = F_E/F \tag{17.27}$$

$$f_Q = F_Q/F \tag{17.28}$$

The fractions of fuel consumption associated with the electrical and thermal energy products relate as follows: $f_E + f_Q = 1$.

17.5.3. Energy-Based Considerations in Allocating CO_2 Emissions for Cogeneration

Using an energy basis, the fuel consumption associated with generating electricity in a cogeneration process can be expressed as

$$F_E = E/\eta_E \tag{17.29}$$

where η_E denotes the energy efficiency of generating the electrical energy product within a cogeneration process. Correspondingly, the fuel consumption associated with producing the thermal energy in the cogeneration process can be expressed as

$$F_Q = Q/\eta_Q \tag{17.30}$$

where η_Q denotes the energy efficiency of producing the thermal energy product within a cogeneration process. Combining the above equations, we can write the following expressions for the fractions f_E and f_Q:

$$f_E = (E/\eta_E)/(E/\eta_E + Q/\eta_Q) \tag{17.31}$$

$$f_Q = (Q/\eta_Q)/(E/\eta_E + Q/\eta_Q) \tag{17.32}$$

17.5.4. Exergy-Based Considerations in Allocating CO_2 Emissions for Cogeneration

Alternatively, we can use an exergy basis rather than an energy basis in establishing the above equations. Then, the fuel exergy consumption, Ex_{FE}, associated with generating the electrical exergy, Ex_E, in the cogeneration process can be expressed as

$$Ex_{FE} = Ex_E/\psi_E \tag{17.33}$$

where ψ_E denotes the exergy efficiency of generating the electrical energy product within the cogeneration process. Correspondingly, the fuel exergy consumption, Ex_{FQ}, associated with producing the thermal exergy, Ex_Q, in the cogeneration process can be expressed as

$$Ex_{FQ} = Ex_Q/\psi_Q \tag{17.34}$$

where ψ_Q denotes the exergy efficiency of producing the thermal energy product via cogeneration. Combining the above equations, we can write the following expressions for the fractions f_E and f_Q, using exergy terms:

$$f_E = (Ex_E/\psi_E)/(Ex_E/\psi_E + Ex_Q/\psi_Q) \tag{17.35}$$

$$f_Q = (Ex_Q/\psi_Q)/(Ex_E/\psi_E + Ex_Q/\psi_Q) \tag{17.36}$$

17.5.5. Advantages of Allocating Cogeneration CO_2 Emissions Using Exergy over Energy

Trade-off between Thermal and Electrical Products of Cogeneration

When an electrical generation process is modified so that it becomes a cogeneration process, some of the electrical product is sacrificed for a gain in thermal output. When considering energy quantities, the thermal energy gain is often very great, even for a small decrease in electrical output. In addition, there is often no dependence on the temperature at which the thermal energy is delivered. When considering exergy quantities, however, the trade-off between electrical and thermal exergy products is more balanced. That is, a small decrease in electrical exergy output usually leads to a relatively small and similar magnitude increase in thermal exergy output, while a large decrease in electrical exergy output usually leads to a correspondingly large increase in thermal exergy output. Furthermore, the increase in thermal exergy is directly dependent on the temperature at which the thermal energy is delivered; generally, the greater is the temperature the greater is the thermal exergy.

For example, a previous study (Rosen, 1990a) of the effects of modifying a coal-fired electrical generating station for cogeneration showed that the overall variation in exergy efficiency is relatively small, while the corresponding variation for the energy efficiency is large. These results are illustrated in Table 17.3, where the exergy efficiencies are seen to vary between 35 and 39%, while the energy efficiencies vary between 37 and 69%.

An interesting observation can be drawn from Table 17.3. The exergy results demonstrate that the benefits of cogeneration are not really due to the shift from electricity generation to heat production, since there is a balanced trade-off between the exergy of the two product commodities, and the overall exergy efficiency remains relatively fixed. Rather, the benefits of cogeneration are due to the fact that the heat produced offsets the need for a separate heat production process that uses additional fuel and—on an exergy basis—is inefficient. The energy results present an entirely different perspective, one that is skewed due to the fact that energy analysis values electrical and thermal energy equally.

Implications for CO_2 Emissions Allocations

The observation that a decrease in electrical exergy output of a cogeneration plant usually leads to a relatively similar magnitude increase in thermal exergy output, but that a decrease in electrical energy output of a cogeneration plant usually leads to a dissimilar magnitude increase in thermal energy output, suggests the following:

- The exergy efficiency of cogenerating the electrical product, ψ_E, is similar to the exergy efficiency of cogenerating the thermal product, ψ_Q.
- The energy efficiency of cogenerating the electrical product, η_E, is not similar to the energy efficiency of cogenerating the thermal product, η_Q.

As a consequence of the above two points, it can be seen from the analyses presented earlier that

- the allocation method based on product exergy contents (Section 17.4) most closely approximates the allocation expressions presented in Sections 17.5.1 through 17.5.3.
- the other emissions allocation methods in Section 17.4 are significantly inaccurate relative to the objective of allocating emissions fairly and accurately.

These two bullets are further discussed in the next section, where the emission allocation methods of Section 17.4 are compared, accounting for the information in this section.

The analysis in this section suggests that the exergy-based allocation method provides a rational means to determine the more productive modifications for a plant, when the objective is to reduce CO_2 emissions.

Other Advantages of Basing CO_2 Emission Allocations for Cogeneration on Exergy

Another advantage of the method of allocating CO_2 emissions for cogeneration processes based on the exergy content of the products is that the allocation method is generalizable to any number and type of products. Most of the other allocation methods in Section 17.4 are much less flexible. For instance, the exergy-based method can accommodate:

- cogeneration processes with multiple electricital and thermal outputs,
- trigeneration processes (i.e., cogeneration processes in which, in addition to electricity and heat outputs, cooling capacity is also a product), and
- other processes producing two or more products (e.g., a fuel production process to produce hydrogen which also yields pure oxygen as a product or by-product, or a chemical process yielding different chemical commodities).

Table 17.3. Variation in overall energy and exergy efficiencies for an electricity generating station when converted to various types of cogeneration*

Operating mode	Temperature of product thermal energy (°C)	Energy efficiency (%)	Exergy efficiency (%)
Electricity generation only	–	37	37
Low-temperature cogeneration**	36	69	39
Intermediate-temperature cogeneration**	243	60	37
High-temperature cogeneration[2]	383	55	35

* Based on data in Rosen (1990a).

** For cogeneration cases, 50% of the resulting process heat is assumed to be useful product.

17.5.6. Comparison of CO_2 Emission Allocation Methods for Cogeneration

Based on the results in this section, the author proposes that the most rational and meaningful method of allocating carbon dioxide emissions for cogeneration is based on the exergy contents of the products. To justify this view, the different emissions allocation methods for cogeneration in Section 17.4 are compared. In particular, the problems inherent in the other CO_2 emission allocation methods for cogeneration processes are discussed.

The allocation method based on energy contents (Section 17.4.1) leads to inaccurate breakdowns of the carbon dioxide emissions, essentially because such a method presumes that the energy efficiency of generating the electrical product within a cogeneration process, η_E, is approximately similar to the energy efficiency of generating the thermal product within the cogeneration process, η_Q. As discussed earlier (Section 17.5.5), this presumption is not valid, as values for η_E and η_Q can vary widely.

The allocation method based on shared emission savings between electrical and thermal energy (Section 17.4.6) leads to inaccurate breakdowns of the carbon dioxide emissions, essentially because the method presumes that the energy efficiency of generating the electrical product within a cogeneration process, η_E, is approximately similar to the energy efficiency of generating the electrical product via a separate process, η_{pp}. This presumption is invalid, as values for η_E and η_{pp} normally vary widely. Similarly, this allocation method presumes that the energy efficiency of generating the thermal product within a cogeneration process, η_Q, is approximately similar to the energy efficiency of generating the thermal product via a separate process, η_b, again an invalid presumption, as values for η_Q and η_b normally vary widely. It makes sense that these efficiencies vary since a key reason to consider cogeneration is that it allows two products to be generated simultaneously with a higher efficiency than if each product were produced separate and independent processes.

Note that one could determine the shared-emissions allocations (Section 17.4.6) based on exergy, rather than energy. Doing so would in fact overcome many of the problems associated with the shared-emissions allocation method based on energy. This is because the exergy-based efficiencies for electricity generation in the part of a cogeneration system responsible for electricity generation and in a pure electricity generation process are similar (i.e., $\psi_E \approx \psi_{pp}$), while the exergy-based efficiencies for thermal energy production in the part of a cogeneration system responsible for thermal energy production and in a pure thermal energy production process are similar (i.e., $\psi_Q \approx \psi_b$). Thus, the shared-emissions allocation method based on exergy reduces approximately to the allocation method based on product exergy.

The allocation methods based on incremental fuel consumption to either electrical production (Section 17.4.4) or thermal production (Section 17.4.5) both lead to inaccurate breakdowns of the carbon dioxide emissions. The reasons are similar and follow below:

- The method based on incremental fuel consumption to electrical production presumes erroneously that the energy efficiency of generating the thermal product via cogeneration, η_Q, is approximately similar to the energy efficiency of generating the thermal product via a separate process, η_b. Still worse, the method then presumes that the energy efficiency value for generating the electrical product via cogeneration, η_E, can be selected so that the overall emissions total correctly. The ensuing values of η_E can as a result vary radically and for the most part arbitrarily.

- Similarly, the allocation method based on incremental fuel consumption to thermal energy production presumes erroneously that the energy efficiency of generating the electrical product via cogeneration, η_E, is approximately similar to the energy efficiency of generating the electrical product via a separate process, η_{pp}. Further, the method then presumes that the energy efficiency value for generating the thermal product via cogeneration, η_Q, can simply be selected so that the overall emissions total correctly. As for the values of η_E in the preceding bullet, the ensuing values of η_Q can as a result vary significantly and for the most part arbitrarily.

In general, the effect of the incremental-based allocations is that they arbitrarily underestimate the emissions from one of the products of a cogeneration process at the expense of the other. Both incremental-based allocations methods are thus unfair, since we seek the true and fair distribution of emissions among products—based on the efficiency of production for each within the cogeneration process.

It is noted that one could determine the incremental-based allocations (Sections 17.4.4 and 17.4.5) based on exergy. However, this determination is not carried out here since the incremental allocation method is itself somewhat arbitrary and therefore not rational.

A common problem shared by the two incremental-based allocation methods (Sections 17.4.4 and 17.4.5) and the shared-emissions allocation method (Section 17.4.6) is that they introduce independent devices for providing thermal energy (e.g., a reference steam boiler) and electrical energy (e.g., a reference power plant). The results obtained using these allocation methods are dependent on the energy efficiencies of these independent devices (η_b for the reference steam boiler and η_{pp} for the reference power plant). But, the values of η_b and η_{pp} can vary notably depending on the specific devices chosen (e.g., high- versus medium- versus low-efficiency models), and these variations cause the emissions allocations evaluated with these methods to vary over correspondingly wide ranges.

The allocation method based on product economic values (Section 17.4.3) leads to inaccurate breakdowns of the carbon dioxide emissions because that method allows economic parameters to skew the allocations. The proper allocations of carbon dioxide emissions for cogeneration should be based entirely on thermodynamics. Economic parameters such as costs and prices vary with time and location, but proper emissions allocations do not as they are dependent on characteristics of the technology involved. If one nevertheless chooses to modify the appropriate emissions allocations by penalizing certain products in terms of their emissions, through economic or other means, then it must be recognized that the resulting emissions allocations deviate arbitrarily from the appropriate emissions allocations.

Similarly, the allocation method based an agreement between the various stakeholders in a project (Section 17.4.7) leads to inaccurate breakdowns of the carbon dioxide emissions because that method allows arbitrary factors that generally are not based entirely on thermodynamics to affect the allocations. If one nevertheless chooses to modify the appropriate emissions allocations by penalizing certain products in terms of their emissions, through factors such as agreements between various stakeholders, it should be recognized that the resulting emissions allocations likely deviate arbitrarily from the appropriate allocations.

In summary, it is pointed out that all of the allocation methods described in Section 17.4, except the one based on exergy, assign some arbitrary and/or subjective values to the differences between the product commodities. We need, instead, a rigorous scientific method, to help get the correct allocation and to remove the arbitrariness, and the exergy approach provides such a method. If, after determining the exergy-based allocations of CO_2 emissions, we nevertheless choose to allocate emissions differently—for economic, political or other reasons—we can do so, but at least we do so knowing the appropriate unbiased allocation.

17.6. Analogy between Allocating Carbon Dioxide Emissions and Economic Costs for Cogeneration

As pointed out earlier, relations between economics and thermodynamics, especially via exergy, have been recognized and led to methods such as thermoeconomics and exergoeconomics. An objective of exergoeconomics, when applied to cogeneration, is determining the appropriate allocations of system costs to the co-products. The costs include both fixed capital costs and operating costs such as fuel costs. An understanding the proper allocations of costs is important because it allows individual product prices to be established that cover the costs of producing the products and allow for a margin or profit. Also, such an understanding identifies when product prices are below cost.

An outcome of many exergy and economic studies is that the most appropriate allocation of costs among cogeneration products is based on the exergy contents of the products. Other cost allocation methods, particularly those based on energy, are inadequate in that they divide costs in ways that radically differ from market prices.

Clearly, then, there appears to be an analogy between the exergy-based method proposed here for allocating carbon dioxide emissions for a cogeneration system, and the exergy-based methods for allocating costs. This analogy may provide insights that allow costs and carbon dioxide emissions to be more appropriately allocated and better understood.

17.7. Closing Remarks

The exergy-based allocation method for carbon dioxide emissions allows for a rational and meaningful allocation for cogeneration systems, and is advantageous to several other proposed methods. By permitting carbon dioxide emissions to be allocated more appropriately among the cogenerated commodities, the exergy-based method allows the environmental benefits of technologies that produce multiple products to be better understood and exploited. The method should therefore allow the more beneficial among competing technologies to be identified in a rational and meaningful manner. Indirectly, due to the analogy between cost and emissions allocations, the method may also lead to economic benefits, as it may permit the costs associated with cogeneration technologies to be more appropriately allocated among the different commodities generated.

As a consequence, the exergy-based method should be used in allocating carbon dioxide emissions for cogeneration devices. Using this method helps ensure proper decision-making regarding issues such as how emissions can be reduced in a given device, how and where cogeneration technologies should be used, and what effect introducing cogeneration can have on overall carbon dioxide emissions. The method is thus useful to designers of energy systems and to decision and policy makers in companies and government, and should allow benefits to accrue to society through the selection and design of better energy technologies, based on environmental considerations.

The allocation method described in this chapter is illustrated through a comprehensive case study in Section 22.2. It is further demonstrated there that the exergy-based emissions allocations method provides a sensible basis for a meaningful overall approach for emissions trading, which leads to a fair way to establish trading schemes.

Chapter 18

ASSESSING ENVIRONMENTAL IMPACTS OF AEROSPACE OPERATIONS WITH EXERGY

OVERVIEW

Aerospace operations are investigated by considering a typical turbojet engine. An exergy analysis of the engine during cruise conditions is presented, and the effects are examined on exergy parameters and environmental and ecological performance of using different reference environment models. The portion of the exergy loss with the exhaust, the largest of exergy loss in a turbojet, varies significantly with reference environment, as does its breakdown into physical, kinetic and chemical components. The environmental and ecological insights offer possibilities to improve exergy efficiency and reduce fuel use and emissions, and identify the potential environmental impact associated with waste exergy emissions, which are exhausted directly into the atmosphere at various altitudes.

An exergy analysis is described of a typical aerospace engine, a turbojet, operating in cruise mode. The effects on exergy parameters and environmental and ecological performance of different reference environment models are discussed, and environmental and ecological insights are described, in terms of potential to improve exergy efficiency and reduce fuel use and waste exergy emissions.

18.1. EXERGY ANALYSIS

The aerospace engine is based the open Brayton cycle, where thrust production generally involves the ejection of exhaust gases at high temperatures and velocities. This operation leads to large exhaust exergy losses, which differ from the exergy losses due to irreversibilities within the system. Understanding the losses is important for improving environmental performance, via increasing efficiency and reducing the exergy associated with unrestricted waste emissions to the environment. The large exhaust loss typical of aerospace engines leads to low exergy efficiencies and environmental concerns.

Exergy analysis has been applied to turbojet, turbofan, scramjet and other aerospace engines (Clarke and Horlock, 1975; Lewis, 1976; Curran, 1973; Brilliant, 1995a, 1995b;

Murthy 1994; Malinovskii, 1984; Riggins, 1996a, 1996b, 1996c, 1997; Riggins and McClinton, 1995; Kotas, 1995; Moran, 1989; Etele and Rosen, 1999; Roth and Mavris, 2001, 2003a, 2003b; Roth, 2002; Moorhouse, 2003; Figliola et al., 2003; Paulus and Gaggioli, 2003; Munoz and Von Spakovsky, 2003; Bejan, 2003; Hallinan et al., 2005; Li and Figliola, 2004; Dincer and Rosen, 2007; Amati et al., 2006, 2007, 2008).

18.1.1. Description of Engine

A typical turbojet engine is considered, as shown in Figure 18.1 with the main devices and state points. Ambient air enters the inlet diffuser and is compressed. The compressed air and fuel enter the combustion chamber, where they react chemically. The combustion gases expand first through a turbine, providing compressor work, and then through the exit nozzle, which converts them to a high-speed jet.

18.1.2. Analysis

We examine engine operation at cruise conditions, assumed to be at an altitude of 15,000 m. The reference environment is selected to be the operating environment at this altitude.

Since the reference environment by definition has no exergy, the exergy of the ambient air is zero. Thus, the input exergy to the turbojet engine is provided by fuel and is mainly in the form of chemical exergy. The fuel may have a small amount of physical exergy due to the difference between the fuel storage conditions and the reference environment.

The exergy efficiency ψ is used here as a measure of merit, defined as the ratio of useful or desired work obtained from the system (thrust for a turbojet engine) to the total quantity of incoming exergy (Clarke and Horlock, 1975; Murthy and Ravichandran, 1996; Czysz and Murthy, 1991).

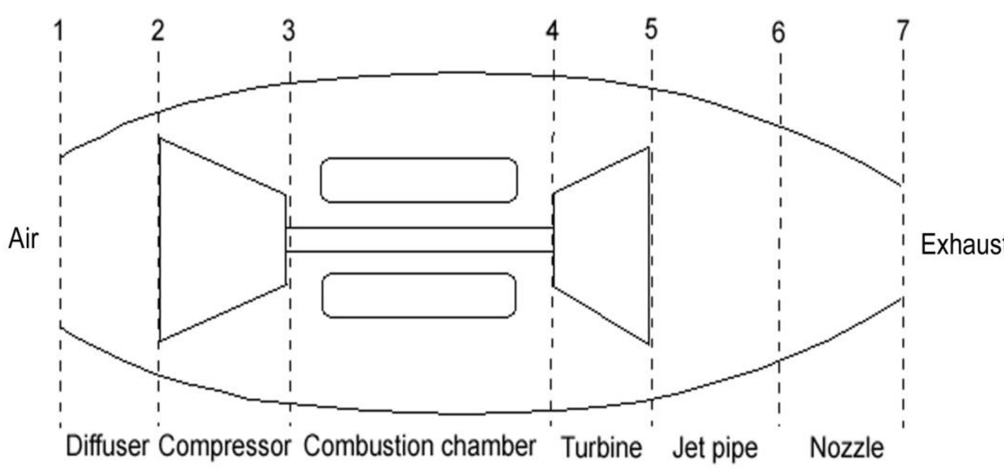

Figure 18.1. Typical turbojet engine showing main components and state points.

Table 18.1. Exergy quantities at outlets of engine components at operating and reference environments of 15,000 m

Component	State point	Power (kW)	
		Shaft	Thrust
External diffuser	1	–6	0
Internal diffuser	2	–13	0
Compressor	3	12	18
Combustor	4	10	285
Turbine	5	14	3
Jet pipe	6	–18	1
Nozzle	7	197	20

Table 18.2. Exergy quantities at outlets of engine components at operating and reference environments of 15,000 m

Component	State point	Specific exergy (kJ/kg)				Energy flow rate (kW)
		Physical	Kinetic	Chemical	Total	
Freestream	0	0	0	0	0	0
External diffuser	1	6	0	0	6	6
Internal diffuser	2	16	4	0	19	20
Compressor	3	186	1	51,200	51,387	52,672
Combustor	4	1123	0	20	1143	1172
Turbine	5	911	2	20	934	957
Jet pipe	6	930	0	20	950	974
Nozzle	7	393	325	20	739	757

To better understand turbojet engine losses, for improving engine efficiency and reducing environmental impact, it is insightful to divide the total exergy loss into waste exergy emissions (e.g., exergy discarded by the turbojet with the exhaust gases) and internal exergy consumptions due to irreversibilities within the engine and its components. Waste exergy emissions are often the single largest loss in a turbojet, so it is informative to subdivide this loss into its main components which, for a turbojet engine, are kinetic, chemical and physical.

18.1.3. Exergy Performance

The shaft and thrust power values for each component of the engine are listed in Table 18.1. The shaft power produced by the turbine is entirely used to drive the compressor, so the net shaft power produced by the engine is zero. The thrust power associated with the exhaust jet exiting the nozzle is 197 kW.

Exergy flow rates and specific exergy flows at points in the turbojet are given in Table 18.2. The specific exergy flows are divided into physical, kinetic and chemical components. Chemical exergy is significant for the fuel and kinetic exergy for the nozzle jet, while physical exergy is large for the compressed and heated flows, i.e., for post-compressor flows.

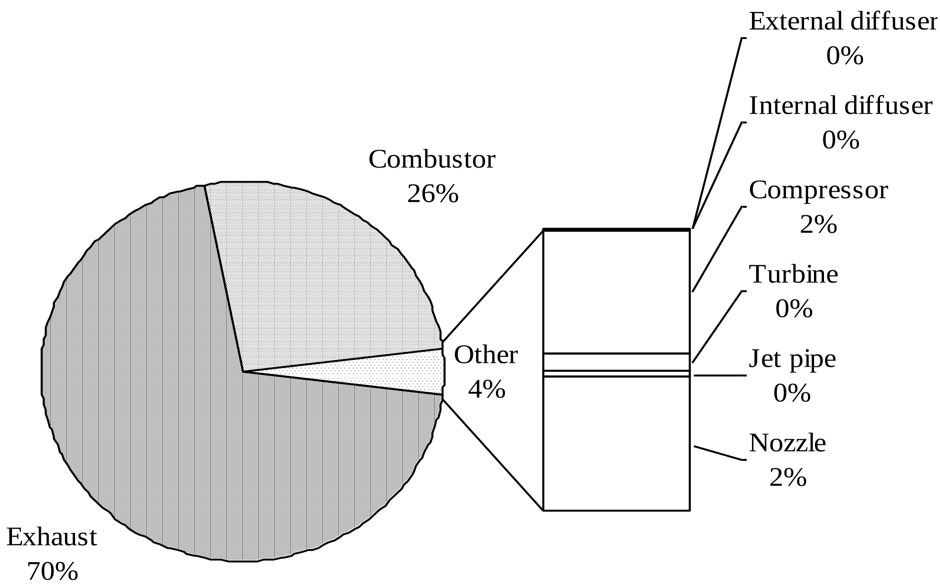

Figure 18.2. Breakdown of the exergy loss rate of the turbojet, which totals 1083 kW, by component and flow.

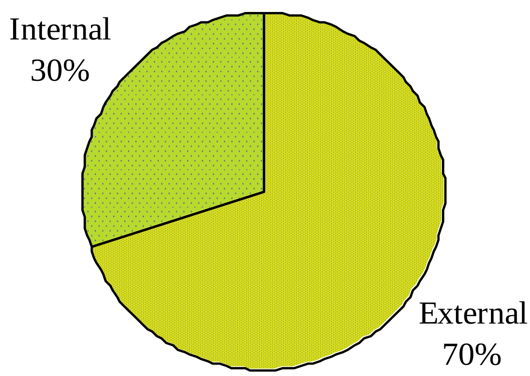

Figure 18.3. Breakdown of overall turbojet engine exergy losses into external and internal components for operating and reference environments at 15,000 m altitude.

The exergy efficiency of the overall turbojet engine is 15.4%, and the exergy loss rate is 1083 kW. A breakdown of the exergy loss rate by component/flow is shown in Figure 18.2.

The exhaust loss is the primary contributor to turbojet inefficiency, and combustion is the second greatest contributor. Most efforts to increase the thrust of a turbojet also increase the exhaust loss (e.g., increasing the exhaust gas temperature and/or velocity to produce more thrust). However, this emission loss is different than losses due to internal irreversibilities (e.g., combustion, friction, pressure loss, mixing) which exist in any real system. The external loss incurred through the ejection of exhaust gases is somewhat recoverable.

The division between internal and external exergy losses for the turbojet engine is shown in Figure 18.3. Since the exergy efficiency is 15.4%, the exergy loss rate is 100 – 15.4 =

84.6% of the input exergy rate. Of this loss rate, 70% is external (ejected with exhaust gases), and 30% internal (consumed due to irreversibilities).

Since exhaust emission is the largest contributor to the overall exergy loss of the engine, it represents the greatest possibility for increased efficiency as well as the main area for reducing environmental impact. To consider improvement options related to the exergy from the exhaust, it is useful to understand the makeup of that exergy flow. The exhaust gas exergy emission for operating and reference environments of 15,000 m is divided in Figure 18.4 into kinetic, physical and chemical components, and each component is described separately:

- Physical exergy, i.e., the exergy obtained by reversibly bringing a flow to thermal and mechanical equilibrium with the reference environment, makes up most of the exhaust exergy (53%). Here, the physical exergy is entirely thermal since the exhaust gases are expanded to the operating environment pressure. However, if there had been a fixed geometry nozzle (hence a constant exhaust pressure), a portion of the physical exergy in the exhaust would be due to the pressure difference between the exit and the reference environment.
- The second largest exhaust exergy component is the kinetic exergy of the expelled gases, which account for 44% of the exhaust loss. Two factors (the high temperature and velocity of the expelled gases) cause the exhaust to contribute greatly to overall engine loss, but these are the characteristics that allow the engine to produce thrust.
- The chemical exergy in the exhaust stream is only 3% of the total exhaust exergy. Since fuel exergy is purely chemical (the physical and kinetic components being small), the exhaust exergy might be expected to contain much chemical exergy. However this is not the case here, becuase the exhaust is non-combustible (i.e., complete combustion is assumed in this analysis). Thus the only chemical exergy present in the exhaust is due to the difference in mole fractions of the exhaust gases leaving the turbojet and the same constituents in the reference environment. The chemical exergy would constitute a greater proportion of the exhaust gas exergy if it contained unburned or partially burned fuel.

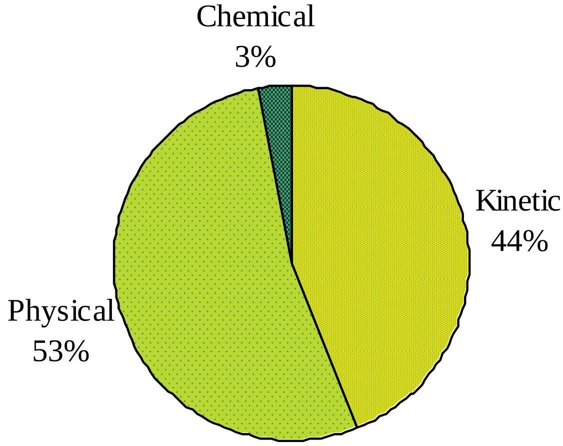

Figure 18.4. Breakdown of exhaust gas exergy emission into kinetic, physical and chemical components for operating and reference environments of 15,000 m.

The key results of the exergy analysis are that the turbojet engine has an exergy efficiency of about 15%, that exhaust emissions are responsible for the majority of the exergy loss, and that the exhaust emission exergy losses are mainly physical and kinetic.

18.2. Effect of Reference Environment Variations

A challenge in exergy analyses of aerospace devices is that the reference environment, which needs to specified for the analysis, varies spatially – especially with altitude. This distinguishes aerospace and ground-based applications of exergy analysis significantly. The reference environment is often modeled as the ambient environment, as this is the actual environment in which the system operates and with which all exchanges of matter and energy occur. Whereas this environment normally remains relatively constant in practice for ground-based systems, ambient operating conditions vary notably during a flight. In many aerospace exergy analyses, a fixed environment is used, often based on a typical operating environment of the engine. Although this approach usually is adequately accurate for ground-based systems, variations in ambient pressure and temperature over the operating range of aerospace engines (sea level to 15,000 m and even in some cases to the near absolute zero temperature and vacuum conditions of space) can affect the accuracy of exergy analyses.

The selection of a reference-environment model involves a trade-off. The use of a fixed reference environment, set at some operating environment, has the advantages of reduced calculation complexity and the ability to straightforwardly assess the engine over flight altitudes ranging from ground level to low Earth orbit and beyond. But use of a fixed reference environment has the disadvantage of being different from the actual environment in which the system operates. The effect on exergy analyses of varying the reference environment is discussed in Section 6.5, and has been considered in several exergy analyses of aerospace systems (Etele and Rosen, 1999, 2001; Rosen and Etele, 2004; Rosen, 2009).

18.2.1. Analysis

The impact of a reference-environment model on exergy-based performance is described in this section for aerospace engines, drawing heavily on previous reports (Etele and Rosen, 1999, 2001; Rosen and Etele, 2004; Rosen, 2009). For simplicity, we examine the typical turbojet assessed in the previous section, for four cases that span its operation range:

- An operating environment fixed at the reference environment condition at an altitude of 0 km (sea level)
- An operating environment fixed at the reference environment condition at an altitude of 15 km (a typical cruise altitude)
- An operating environment at an altitude of 15 km and a reference environment at an altitude of 0 km
- An operating environment at an altitude of 0 km and a reference environment at an altitude of 15 km

Table 18.3. Turbojet engine performance parameters for various operating and reference environments

Engine performance parameter	Reference environment altitude 0 km		Reference environment altitude 15 km	
	Operating altitude 0 km	Operating altitude 15 km	Operating altitude 0 km	Operating altitude 15 km
Thrust power (kW)	226	197	226	197
Exergy loss rate (kW)	1070	925	1205	1083
Exergy efficiency (%)	16.9	17.5	15.3	15.4

Table 18.4. Breakdown of turbojet engine exergy losses (in %) for various operating and reference environments

Exergy loss	Reference environment at 0 km		Reference environment at 15 km	
	Operating altitude 0 km	Operating altitude 15 km	Operating altitude 0 km	Operating altitude 15 km
Internal	35	48	22	32
External	65	52	78	70

Table 18.5. Breakdown of external exergy loss (in %) for turbojet engine for various operating and reference environments

External exergy loss	Reference environment altitude 0 km		Reference environment altitude 15 km	
	Operating altitude 0 km	Operating altitude 15 km	Operating altitude 0 km	Operating altitude 15 km
Physical	52	25	65	53
Kinetic	44	69	33	44
Chemical	4	6	2	3

When the operating and reference environment conditions change simultaneously, the situation is akin to one in which we have a variable reference environment that is modeled as the changing operating environment. The results in these cases are meaningful, in that they emulate reality. Of the four cases considered here, the ones in which the operating and reference environment conditions are fixed at those for an altitude of 0 km, and then at an altitude of 15 km, fit into a variable reference environment. The other two cases considered (an operating environment of 0 km in a reference environment at 15 km, and an operating environment of 15 km in a reference environment at 0 km) are inconsistent with the notion of a variable reference environment, but may be utilized in analyses when one wishes for simplicity to use a fixed reference environment in an assessment.

18.2.2. Sensitivity of Exergy Parameters to Reference Environment Selection

Performance parameters for the turbojet engine for the four pairs of operating and reference environments are given in Table 18.3. Variations in thrust power of up to 15% are observed as the operating environment changes from sea level to 15 km. Furthermore, for the operating and reference-environment conditions considered, variations in the exergy loss rate are as high as 22% while variations in the exergy efficiency are as high as 15%.

Note that different merit measures can be used – although confusion can result due to these differences. For instance, the exhaust exergy can be treated as a necessary flow for the device, and not as a loss. This approach avoids penalizing the engine for the exhaust loss, considering that loss attributable not to the engine but rather to the cycle in which it is employed. Here, we use the combined overall loss to reflect the fact that the exhaust possesses exergy that a designer should recognize.

Exergy losses for turbojet the engine are divided into internal or external losses in Table 18.4, for the four pairs of operating and reference environments considered. The breakdown is strongly dependent on the choice of reference environment, with the internal exergy loss ranging from as low as 22% of the total exergy loss to as high as 48%, while the external exergy loss rate ranges from 52% to 78% of the total exergy loss rate.

External exergy losses for the turbojet are broken down by component (physical, kinetic, chemical) in Table 18.5 for the four pairs of operating and reference environment altitudes considered. The breakdown depends notably on the choice of reference environment. The physical exergy associated with the exhaust exergy emission ranges from as low as 25% to as high as 65% of the exhaust exergy emission, while the corresponding range for the kinetic exergy component is 33% to 69%. The chemical exergy component is relatively small for all cases considered, by still varies notably on a percentage basis between 2% and 6%.

The choice of reference environment has a significant impact on the accuracy of exergy analysis results, especially the locations and causes of exergy losses. Specifically,

- The overall internal losses (attributable to irreversibilities within the engine) decrease with altitude when using a variable reference environment. But, the use of a constant reference environment leads to differences as great as 18% in the exergy loss with exhaust emissions. Further, using a fixed reference environment with parameters corresponding to low-altitude conditions leads to an under-prediction of the exhaust loss at all altitudes except the reference altitude, whereas the opposite is true if the reference environment parameters are fixed at conditions for higher altitudes.
- Although the magnitude of the exhaust exergy loss varies with altitude, its composition remains nearly constant when a variable reference environment is used. But use of a constant reference environment makes the exhaust loss breakdown dependent on altitude. A reference environment different than the operating environment (whether higher or lower) causes the physical component of the exhaust loss to decrease with increasing altitude and the kinetic contribution to increase. The differences of the actual and indicated component contributions can reach 28%.

18.3. Environmental and Ecological Implications

Exergy analysis provides for aerospace technologies and operations a good understanding of both inefficiencies and the potential for efficiency improvement they provide, as well as the exergy associated with waste emissions. The latter are crucial for aerospace engines in that exhausts are inherent to many types (e.g., turbojets and turbofans), and the emission occurs at various locations in the atmosphere, ranging from ground level to the stratosphere, with some of the atmospheric locations exhibiting high sensitivities to certain emissions. The exergy associated with losses provides some indications of the potential for environmental and ecological impact associated with aerospace technologies and operations that, in concert with other information, can help inform the design of cleaner technologies.

For analysis and design work, the use of a constant reference environment appears unsuitable in many instances for accurately guiding improvement efforts, as the locations of the greatest losses and the causes of these losses are not properly characterized. The proper method to use in assessing aerospace systems is one in which the reference environment varies in line with variations in the natural environment as altitude changes. Before constant reference environments are used as simplifications, the potential errors that may be introduced should be assessed. Care should be exercised when a constant reference environment is utilized to simplify calculations, given the inaccuracies that may ensue.

The present work considers altitudes up to 15,000 m, but the inaccuracies of using a constant reference environment are greater at higher altitudes, where the operating environment differs even more from that at ground level.

18.4. Closing Remarks

The investigation of a turbojet, a typical aerospace engine, using exergy methods provides insights into the performance, efficiency and environmental and ecological impact of the device. The effect of reference environment selection, which is complex for aerospace engines, is seen to have a significant effect on analysis results. Environmental and ecological insights are provided by the analyses, in terms of potential to improve exergy efficiency and thereby reduce fuel use, as well as the potential environmental impact associated with waste exergy emissions, which are exhausted directly into the atmosphere at various altitudes.

Chapter 19

ENVIRONMENTAL PLANNING WITH EXERGY

OVERVIEW

Environmental planning takes into consideration many factors, sometimes including thermodynamics. Efforts to better understand and reduce environmental impact often can be enhanced by combining thermodynamics with environmental disciplines. Most such assessments consider thermodynamics in terms of energy, despite the advantages of using exergy. Consequently, exergy may provide a meaningful and useful tool in environmental planning. Techniques that integrate exergy, ecological and environmental factors are related to environmental planning in this chapter, and correlations between exergy and environmental parameters are utilized to demonstrate that exergy factors into environmental improvement. As exergy-based methods can help determine appropriate environmental improvement measures, their links to environmental planning are increasingly evident and important.

Environmental and ecological impacts are important considerations in environmental planning. Such considerations are also important in other areas such as the analysis, design and optimization of technologies. The latter activities often utilize techniques that combine technical disciplines like thermodynamics, usually in terms of energy, with environmental and ecological disciplines. Hence, environmental planning activities that incorporate thermodynamic factors often do so in terms of energy.

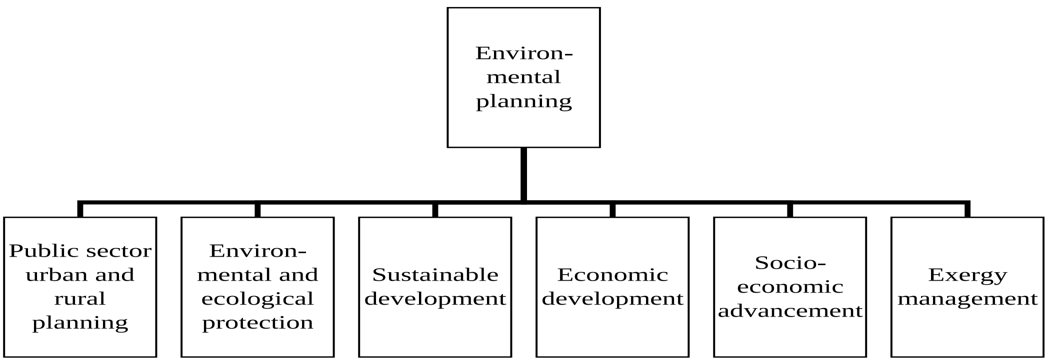

Figure 19.1. Factors in environmental planning.

Energy generally is not an indicator of environmental or ecological impact potential. However, the second law of thermodynamics has significant implications for environmental and ecological quality and impact, and thus can be of benefit for environmental planning. Exergy, in particular, has been suggested to provide an indicator of the potential for environmental or ecological impact and to be of use in understanding and assessing ecological wellness, environmental impact, resource depletion and sustainable development. Consequently, environmental and ecological assessments and planning may be better performed utilizing exergy rather than or with energy.

The exergy-based environmental and ecological analysis techniques described in previous chapters, like environomics, exergy-based industrial ecology and exergetic life cycle assessment, can aid in determining appropriate resource allocations for environmentally responsible design and operation. Exergy-based environmental and ecological techniques determine a system’s exergy as well as its inputs and outputs, and can improve designs. Exergy thus has an important role in efforts to improve sustainability.

Planning based on assessments that ignore nature significant deteriorate the ability of ecosystems to provide the goods and services needed for human activity. Understanding these issues is not straightforward, as local, regional and global ecological integrity are complex to understand, assess and maintain, despite being important in efforts to restore the environment and protect human health (Kay and Regier, 2000). Such efforts require ecological model development, including selection of a model structure based on ecological system properties, and involve challenges that are continually being investigated.

In this chapter, we discuss the potential use in environmental planning of relations between exergy, environmental impact and ecological health, and corresponding analysis techniques, and demonstrate how exergy methods may enhance environmental planning. Exergy management is shown in Figure 19.1 as one of the factors in environmental planning.

19.1. Exergy and Planning

The attributes of exergy and the benefits of applying them through exergy analysis make exergy a potentially useful tool in planning. There are several reasons for this perspective:

- The performance and efficiency of industrial systems can be described with thermodynamics and are better assessed with exergy analysis. Conventional energy efficiencies do not always assess how nearly performance approaches ideality and factors which cause performance to deviate from ideality. Exergy efficiencies provide an actual measure of how nearly efficiency approaches ideality, identifies properly the causes, locations and magnitudes of inefficiencies, and indicates theoretical limitations. Thus exergy methods can help in efforts to improve “energy conservation,” energy management and loss reduction. Its illuminating and rational basis allows exergy analysis to assist in planning, by facilitating the improvement and optimization of designs.
- Exergy can be used to improve understanding of economics and to enhance the economic performance of energy and other systems (Rosen, 2011). By linking economics with thermodynamics rationally and meaningfully, useful methods can be

attained for assessing and improving economic viability and profitability. Such exergy-based economics can be extremely useful in planning.

- Exergy can be used to improve understanding of and to enhance management systems like supply and inventory systems (Rosen, 2011). This use of exergy can help improve the efficiency and effectiveness of management systems and activities, and thus can contribute to planning notably. For instance, linkages have been identified between exergy and price-driven economic systems, repair and waste disposal, inventory systems, and diffusion-like economic commodity flows (Jaber et al., 2004, 2006; Jaber and Rosen, 2008; Nuwayhid et al., 2006).
- Exergy can be used to assess and mitigate environmental impact and ecological disruptions, as explained throughout this book. Extending the reference environment of exergy analysis to the natural environment is an important consideration in enhancing the ability of exergy methods to assess and improve environmental and ecological systems and aid environmental planning.

Increasing application of exergy methods has been observed recently, in such areas as chemical processing, electricity generation, cogeneration, HVAC, energy storage, and metallurgical processing. Some leaders in industry and government have begun to recognize the usefulness of exergy methods, and their potential use in planning. This recognition has been observed not just at the industry level, but regionally and nationally, since many exergy analyses have been reported for regions and countries, as well as their sectors.

Although extending exergy concepts to industry leaders and policy makers is still a challenge, a particularly interesting example of the use of exergy in planning is reported by Favrat et al. (2008), who describe the challenge of introducing an exergy indicator in a local law on energy. The authors describe the introduction of a law in Switzerland's Canton of Geneva governing the attribution of building permits for new or retrofitted city areas. Authorities defined a procedure including the calculation of an exergy indicator to be quantified for large projects submitted for acceptance.

19.2. ENVIRONMENTAL PLANNING USING EXERGY AS AN ENVIRONMENTAL INDICATOR

Increasing exergy efficiency reduces environmental impact by reducing resource requirements and emissions. But relations between exergy and the environment can reveal further underlying fundamental patterns affecting environmental changes since exergy is linked to environmental impact through it being a measure of the departure of the state of a system from that of the environment. Exergy is a measure of potential of a substance to cause change, so an emission's exergy can provide a measure of its potential to change or impact the environment. The exergy of an emission is zero only when it is in equilibrium with the environment and thus benign. Furthermore, as discussed in Chapter 17, exergy can also assist in allocating emissions reasonably among the outputs of multi-product systems, by providing a fair approach for attributing the causes of environmental damage. Thus exergy may be, or provide the basis for, an effective indicator of the potential environmental impact of an emission, which can be utilized in environmental planning.

Many of these ideas are not new, as decades ago it was suggested that exergy analyses of natural processes could provide a foundation for ecological planning (Tribus and McIrvine, 1971) and that exergy could be part of air-pollution rating (Reistad, 1970). Subsequent efforts have sought to convert exergy's linkages with pollution and dispersion into a reliable tool on which policy decisions can be based.

The exergy-based environmental methods described earlier are now re-examined from the perspective of environmental planning:

- *Reducing industrial emissions via increased exergy efficiency*: A key aspect of environmental planning is emissions reductions, often by increasing efficiency. Insights provided by exergy analysis are important in environmental planning, as they can help identify where improvement efficiency potential lies and provide policy advice on sustainability (Hammond, 2004). Approaches for improving energy systems design that consider exergy, the environment and economics have been developed (Giannantoni et al., 2005), and an evaluation method has been proposed for the environmental sustainability of industrial processes that uses exergy to combine material and energy streams via a life cycle approach (Yi et al., 2004).
- *Cumulative exergy consumption*: The environmental impact of industrial processes can be assessed for planning via the exergy consumption accumulated over processes. Szargut et al. (2002) suggest that the cumulative consumption of non-renewable exergy provides a measure of the depletion of non-renewable natural resources, a key element of environmental planning. Industrial cumulative exergy consumption evaluates the exergy of all natural resources consumed by economic sectors. Also, cumulative exergy consumption has been extended to ecological cumulative exergy consumption so as to incorporate the contribution of ecosystems, accounting for the exergy consumed in ecological systems in producing natural resources (Hau and Bakshi, 2004; Ukidwe and Bakshi, 2007). The cumulative exergy consumption approach has been used for the treatment of emissions (Zhu et al., 2005), while a generalized resource and ecological evaluation approach has been developed based on embodied exergy, i.e., the cosmic exergy consumed directly or indirectly in creating or sustaining a commodity or service (Chen, 2006).
- *Extended exergy accounting*: By determining the cost of a commodity based on its resource-base equivalent value (including equivalent exergy flows for labor, capital and environmental remediation), extended exergy accounting has been used to assess complex systems and to evaluate environmental externalities (Sciubba, 2001b; Sciubba, 2004). For these reasons, this technique can help in forming pollution policies and environmental planning.
- *Exergy and industrial ecology*: Environmental planning can utilize the concepts embodied in industrial ecology, which include designing industrial systems to balance industrial activity and environmental stewardship, where energy and materials are entirely recycled (Graedel, 1996). Industrial ecology can beneficially incorporate exergy (Connelly and Koshland, 2001a, 2001b; Dewulf and Van Langenhove, 2002; Dincer and Rosen, 2005), enhancing further its benefits in planning. For example, Zvolinschi et al. (2007) apply exergy sustainability indicators as a tool in industrial ecology, while Kay (2002) treats systems of varying complexity, accounting for exergy flows and considering industrial ecology

concepts. For eco-industrial systems, exergy-based indicators of resource-utilization efficiency and environmental-impact potential have been developed and related to industrial ecology (Li et al., 2006).

- *Exergy, life cycle analysis and design for environment*: Life cycle assessment, which can help prevent pollution and improving environmental management, can be extended by considering exergy to exergetic life cycle assessment (Granovskii et al., 2006b, 2007). Exergetic LCA extends the objectives of LCA to considering exergy flows and destructions and options for reducing exergy destructions and increasing exergy efficiency. Also, design for environment methods focus primarily on subjective ranking techniques, but can incorporate exergy methods to provide less subjective metrics (Connelly and Koshland, 1997, 2001a, 2001b).
- *Exergy and ecological footprint and environomics*: Integrating exergy into ecological footprint and environomics assessment methods has made them more useful in environmental planning. For instance, the aggregate indicator ecological footprint has been extended to embodied exergy ecological footprint, which shows the ecological overshoot of ecological systems (Chen and Chen, 2007), while environomics simultaneously accounts for exergy along with energy, economic and environmental factors (Frangopoulos and von Spakovsky, 1993). For biological processes like agriculture, indicators have been developed based on ecosystem thermodynamics, in part by measuring the capacity of an ecosystem to dissipate solar exergy (Wagendorp et al., 2006).

The types of environmental impact predictable using exergy as an environmental indicator can also be used in environmental planning. First, the potential to cause change represented by waste emission exergy provides a measure of potential for environmental harm and accounts for the fact that not all types of emissions pose equal risks. The exergy of emissions can interfere with the solar energy balances on the Earth, contributing to climate change. Second, environmental damage is associated with the degradation of resources found in nature (i.e., destruction of their exergy). Third, a form of environmental damage is associated with the creation of disorder (or a state of low exergy), as a low-exergy system (e.g., carbon dioxide mixed in the atmosphere) is more disordered than one of high exergy (e.g., carbon dioxide in a tank).

These points suggest a role for exergy in environmental planning. Evaluating alternative device options often involves comparisons of their emissions. Existing methods are usually subjective and based on energy, which does not provide a good indicator of environmental impact. Exergy is a more objective indicator for potential environmental impact, partly because emissions only have exergy when in disequilibrium with the environment.

19.3. Environmental Planning Using Exergy-based Ecological Indicators

Exergy is considered by many to be useful for understanding and managing ecological systems. Exergy provides a useful optic because ordered ecosystems have high exergy and disordered systems low exergy. Jorgensen and Svirezhev (2004) interpret thermodynamics in an ecosystem context to explain ecosystem reactions to perturbations, and feel exergy explains ecosystem reactions and growth patterns. Hence, they use exergy to describe ecological reactions and ecosystem health, both of which factor into environmental planning.

Planning can also be enhanced using the ideas that ecosystems seek to maximize exergy dissipation by maximizing internal exergy storage as biomass, biodiversity and complex trophical networks, and that human activity can decrease ecosystem exergy by decreasing biomass or internal complexity, and can convert ordered self-producing ecosystems (e.g., marine estuaries, grasslands) with their resource accumulations (e.g., arable soils, mineral deposits) into damaged and disordered ecosystems (e.g., eroded farmlands, depleted fisheries). The hierarchy of embedded systems for ecosystems, put forth by Nielsen (2000) to facilitate thermodynamic applications, can also facilitate environmental planning.

The use of exergy in ecological models (Jorgensen, 2002a) facilitates its application in environmental planning. Marques et al. (1998) propose exergy as a holistic ecosystem indicator, and ecosystems have been hypothesized to develop according to four attributes that relate to planning: ascendency, exergy storage, ability to dissipate external gradients in exergy, and network aggradation (Ulanowicz et al., 2006). Ecological exergy is often viewed as a system-oriented development indicator, and suggesting a role in environmental planning.

The exergy-based ecological indicators described earlier are now re-examined from the perspective of environmental planning:

- *Structural changes*: Environmental planning can utilize the fact that ecological structural changes appear to be accompanied by increased exergy (Jorgensen, 1988). Bendoricchio and Jorgensen (1997) provide a rationale for applying exergy as goal function, and exergy has been applied in structural-dynamical modeling (Nielsen, 1990). Jorgensen et al. (2002) suggest that an exergy index can be used with ecosystem models to determine which structures prevail for given environmental circumstances, with the structure having the highest exergy prevailing.
- *Ecological processes*: Exergy efficiencies for ecological processes can facilitate improvements in efficiency via planning. Zhou et al. (1996) propose evaluation methods for the exergy in living systems, considering physical-chemical and physiological-ecological processes, and obtain four ecological exergy efficiency indices. Extensions of exergy analysis for life cycle and sustainability evaluations of processes can help planning, but are more holistic and useful if they account for the role of ecosystems in sustaining industrial activity (Hau and Bakshi, 2004).
- *Maturity*: Environmental planning can exploit exergy's use as a measure of ecosystem maturity, e.g., Odum's attributes of ecosystem maturity (Christensen, 1995). A comparison with rankings based on various ecosystem goal functions shows that maturity exhibits a strong negative correlation with relative ascendency, and thus a strong positive correlation with system overhead, a possible measure of ecosystem stability and an important goal of environmental planning.
- *Extremal principles and optimization*: Ecological indices describe ecosystem behavior, often assuming ecosystems optimize exergy. This understanding can aid environmental planning. For instance, exergy has been considered as a constrained optimizing function in a structural dynamical model, and tested on biomanipulation of the phytoplankton community in a shallow lake (Nielsen, 1995). Also, shifts in

composition in a macrophyte society can be understood using exergy (Nielsen, 1997). Four types of exergy (traditional exergy, internal exergy, structural or modern exergy, normalized exergy) have been proposed as goal functions in ecosystem development and optimization. A dynamic structural model able to describe the observed changes in phytoplankton biomass and diversity was tested to determine if ecosystem reactions strive to maximize exergy under prevailing conditions (Jorgensen and Padisak, 1996). Furthermore, extremal principles or ecological orientors or goal functions are commonly used today in theoretical ecology, but can be extended to planning applications. For example, exergy and ascendency are two goal functions, which Ray (2006) optimized in an aquatic ecosystem.

- *Buffering capacity and constraints*: Environmental planning can apply the suggestions that exergy is linked to ecological constraints (Jorgensen, 1992a) and related to the buffering capacity of ecological systems (Jorgensen, 1982).
- *Dissipation*: Biological dissipation, which occurs during respiration, excretion, egestion, natural and predatory mortality, manifests itself as exergy destruction and involves degradation from more to less organized states, affecting the formation of structures, growth and development. Dissipation thus appears useful in environmental planning. For instance, Straskraba et al. (1999) suggest that trophic pyramids and ecological efficiencies account for dissipation, and that environmental concerns are dissipation-driven challenges. Mandal et al. (2007) suggest that the equilibrium of an ecosystem may gradually become chaotic, based on examinations of thermodynamic properties in an ecological model shifting from ordered to chaotic, as well as the exergy of systems oscillating before entering a chaotic situation.
- *Biodiversity*: Ecosystems often adapt when faced with external changes, e.g., new species replace those unable to cope. The use of exergy as goal function provides ecosystem models with the flexibility of real ecosystems, facilitating environmental planning, and somewhat express Darwinian selection thermodynamically (Jorgensen, 1992c). The ecological significance of exergy was tested against biodiversity, an important ecosystem structure characteristic, via spatial and temporal relations for an estuarine gradient of eutrophication (Marques et al., 1997). Although biodiversity interpretations are somewhat subjective, exergy-based goal functions have been proposed for ecological models and as holistic ecological indicators of ecosystems integrity. For instance, Holling proposes an exergy-based approach for ecosystem dynamics as a guide for evaluating the impact of climate change on biodiversity, a measure of species richness and heterogeneity (Hansell and Bass, 1998).
- *Health and quality*: Exergy constitutes a system characteristic that expresses the natural tendencies of ecosystems to evolve and an ecological indicator of ecosystem health, a key objective in environmental planning. For example, exergy and specific exergy of macrophytes have been tested as an integrated index to assess ecosystem health in coastal lagoons (Austoni et al., 2007), while exergy and structural exergy, trophic state index, diversity index and phytoplankton buffer capacity have been considered as measures of ecosystem health (Xu, 1996). Exergy may provide a useful planning tool as unified measure of water quality and pollution (Huang et al., 2007), and chemical exergy may provide a unified objective indicator for water quality,

avoiding the subjective characteristics of conventional indicators and thereby enhancing environmental planning (Chen and Ji, 2007).

Tool boxes for integrated ecological and environmental management, based in part on exergy, have been developed by Jorgensen and Nielsen (2012). The approach involves identifying causes and quantifying all sources of environmental and ecological problems, performing a diagnosis to understand the relation between the problem and the sources, determining the tools needed to address the problem, implementing appropriate measures, and monitoring the recovery process.

Eco-exergy can be used in environmental planning to assess ecosystems. As a modified form of exergy which measures a system's deviation from chemical equilibrium and uses a reference state suitable for ecological applications, eco-exergy can be advantageous. For instance, Jorgensen (2006) proposes, as indicators for ecosystem development and health eco-exergy, specific eco-exergy (the ratio of eco-exergy to biomass), and shows that attributes for ecosystem development and descriptors of ecosystem health are accounted for by growth of biomass, network and information. Eco-exergy storage has been applied to terrestrial ecosystems (Jorgensen et al., 2000; Jorgensen, 2002b; Jorgensen and Svirezhev, 2004), while eco-exergy has been utilized to describe the development of an aquatic ecosystem.

Emergy (the solar energy required directly and indirectly to generate a flow or storage) is related to exergy and can used in assessing ecosystems and related environmental planning. As a thermodynamic method from systems ecology, emergy analysis allows assessments of self-organizing systems such as ecosystems and the biosphere (Bastianoni and Marchettini, 1997). While exergy analysis provides insights like quantified irreversibilities and the matching of inputs and end-uses, emergy analysis focuses on energy and resource flows for ecosystems (Sciubba and Ulgiati, 2005). Exergy and emergy assessments have been compared for ethanol production from corn (Sciubba and Ulgiati, 2005). A particular benefit of the emergy approach is that traditional exergy calculations for higher organisms do not account for organization. Emergy and exergy can be considered complementary objective functions (Bastianoni and Marchettini, 1997), with both able to describe self-organizing systems like ecosystems and thus assist environmental planning. Some methods integrate exergy and emergy, e.g., Jorgensen et al. (2004) evaluate the emergy and exergy of genetic information and its biological carriers, while Patten (1995) combine ecological extremal principles for exergy, emergy and ascendancy. The emergy-exergy ratio for a flow can aid environmental planning since it provides the concentration of solar energy equivalent (emergy) required to maintain or create a unit of organization (exergy), and measures how efficiently a system organizes or maintains its complexity, providing the environmental cost for the production of a unit of organization. For example, the emergy-exergy ratio for coastal lagoons was found to be lowest for a natural ecosystem and highest for a waste pond. It was also shown that maximum emergy and maximum exergy principles in ecosystems both have practical validity and should be applied in sequence (emergy maximization followed by exergy maximization) (Bastianoni et al., 2006).

The relations between exergy and ecology discussed in this section can be incorporated into environmental planning. Exergy-based ecological indicators for ecological processes, like structural changes, maturity, buffering capacity, dissipation, biodiversity, health and quality, give useful information for understanding and managing ecosystems. Eco-exergy provides a useful measure and indicator for ecosystem development and health, while emergy describes self-organizing systems like ecosystems. Methods to plan and manage environmental systems usually are best informed by accounting for all available information, including exergy and ecology relations.

19.4. Environmental Planning using Exergy-based Economic, Environmental and Ecological Relations

Extending the ties between exergy, environment and ecology to economics makes them more relevant to environmental planning. For instance, exergy's links to environmental impact and management can be included in exergy-based economics.

Extending exergy and economics with environmental factors can facilitate reductions in life cycle costs while mitigating environmental effects, as illustrated in prior chapters. Sciubba (2001a, 2003, 2004, 2005) proposes exergoeconomics as a basis for rational resource use, extends exergy accounting and thermoeconomics with environmental factors to improve design, and proposes extended exergy accounting as a costing method using a resource-based quantifier (extended exergy) and environmental remediation costs (equivalent cumulative exergy expenditure to achieve zero impact). Lazzaretto and Toffolo (2004) show how designs can be optimized using objectives relating to energy, exergy, economics and the environment, while Tonon et al. (2006) also proposes a method based on energy, exergy, economic and environmental factors. A carbon exergy tax is proposed to increase the efficiency of exergy resource utilization (Santarelli, 2004). Ferrari et al. (2001) promote exergy-based indicators of sustainable development including economics, while Honkasalo (1998) applies exergy to the economy to model for sustainable development at the macro-economic level.

Exergy-based economics are linked to ecology in ways that can enhance environmental planning. Ecological economics interprets the environment-economy relation in terms of exergy, which views economic activity as dissipative or exergy consuming. One ecological-economic perspective of economic development and environmental protection suggests that the ascendance of humanity is consistently accompanied by an accelerating rate of ecological degradation and that economic development unavoidably conflicts with environmental protection (Rees, 2003), making these ideas important to environmental planning.

Environmental planning can be made more comprehensive and meaningful if it extends to economics of the links between exergy, environment and ecology. The use of exergy-based economic assessments and environmental or ecological impact costs can inform planning, thereby allowing rational decisions that help manage the environment advantageously.

19.5. Illustrations

Applications of exergy in environmental planning have been reported for a wide range of devices, systems and processes that illustrate well its benefits, and are transferrable to environmental planning. For instance, EXCEM analysis, which simultaneously considers exergy, cost, energy and mass, has been applied to such processes as a greenhouse heating system using a solar-assisted ground-source heat pump (Ozgener and Hepbasli, 2005), ground-source heat pumps for buildings (Ozgener et al., 2005b) and geothermal district heating (Ozgener et al., 2007a, 2007b). Also, exergy and environmental analyses have been reported for transport engines for aircraft (Rosen and Etele, 2004) and automobiles (Daniel and Rosen, 2002), while a power plant combining a solid oxide fuel cell and gas turbine was assessed using thermoeconomics and a carbon exergy tax (Santarelli, 2004). Extensions of exergy accounting and thermoeconomics with environmental factors have been applied to gas turbine-based cogeneration (Sciubba, 2001a, 2003), while an exergetic, economic, environmental method has been applied to bioethanol production (Tonon et al., 2006).

Exergy-based ecological models and methods have been applied to various ecosystems. Reliable indicators for assessing the stresses in ecosystems from pollution are necessary, and exergy-based indicators of ecosystem integrity facilitate detection and evaluation of environmental responses to pollution, mitigation of the harmful impacts, and effective ecosystem management and planning. For instance, Zhang and Wang (1998**)** demonstrate that exergy can act as an object function in ecological models for lakes and reservoirs, while Xu (1997) apply exergy and structural exergy as ecological indicators to assess the development of Lake Chao, China, and the restoration of its riparian wetlands and macrophytes. Also, exergy and structural exergy are used to assess the health of Lake Baikal (Silow and Oh, 2004). Exergy and structural exergy are demonstrated to be feasible ecological indicators of system-level responses of lake ecosystems to chemical stresses of acidification and copper and pesticide contamination (Xu et al., 2002). For communities in the bottom of the North Adriatic Sea, exergy has been cited as a useful indicator for integrating the underlying recovery processes of benthic communities after disturbances like controlled trawl fishing (Libralato et al., 2006). Park et al. (2006) use self-organizing maps to pattern the exergy of benthic macroinvertebrate communities in the Netherlands, and suggest that patterning changes of exergy is effective for evaluating ecosystems.

The applications of exergy methods to ecosystems and other environmental systems illustrate their potential uses in environmental planning. The results demonstrate how exergy based methods can provide useful information that guide decisions, and that exergy-based environmental or ecological parameters can act as objective functions or constraints in planning exercises. The uses of these methods in environmental planning are well illustrated through the correlations identified in Chapter 9 by comparing the exergy of waste emissions with air emission limits in Ontario, Canada, and two quantifications of "environmental costs" for fossil fuel combustion emissions (one based on the cost of removing pollutants from a waste stream prior to discharge to the environment, and the other based on quantitative and qualitative evaluations of the cost to correct or compensate for environmental damage and/or to prevent a harmful emission). These comparisons identify trends that may permit the exergy of a substance to be a tool for establishing emission limits that are rationally based rather than formulated by trial and error. This illustration demonstrates that exergy-based ecology and environmental concepts can form part of environmental planning, with respect to measures to assess or control the potential environmental impact of emissions.

19.6. Closing Remarks

Exergy exhibits many interesting and useful relations with the environment and ecology that can be useful in environmental planning. A summary is presented in Figure 19.2 of the many factors involved in exergy management in environmental planning discussed throughout this chapter. Exergy-based relations can provide a foundation for exergy-based environmental and ecological methods, which are useful in analysis, comparison and improvement activities. By integrating thermodynamics with ecology and environmental concepts, the methods can help achieve advantageous designs, noting that environmental and ecological health can be understood using exergy and that environmentally successful systems generally seem to be configured so as to balance appropriately exergy-based economic and environmental and ecological factors. Analogous relations based on energy in general are prone to be misleading since energy is not energy a measure of the potential for ecological and environmental impact. The illustrations suggest that exergy should factor into environmental planning, including environmental remediation and ecological management.

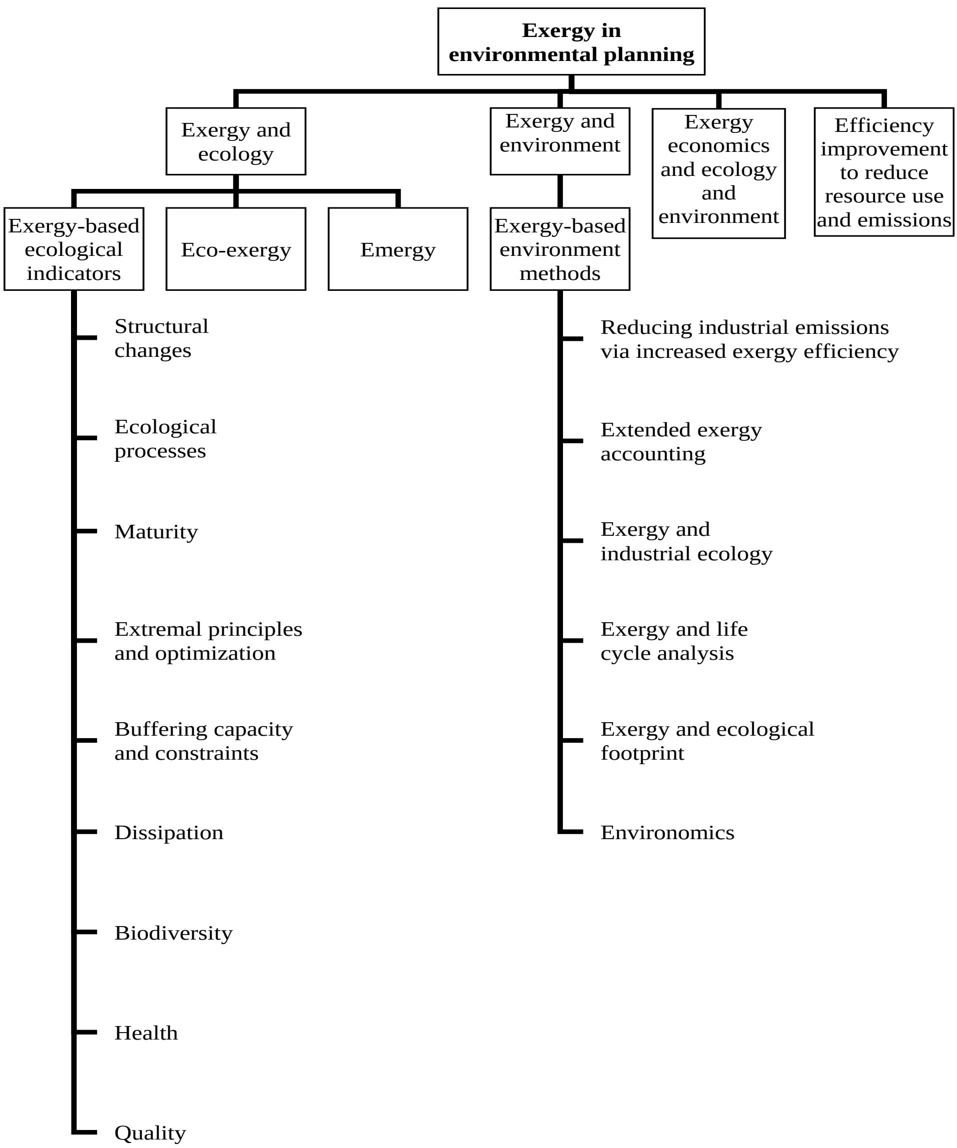

Figure 19.2. Breakdown of factors involved in using exergy in environmental planning.

PART IV: CASE STUDIES

Chapter 20

COAL-FIRED ELECTRICITY GENERATION

OVERVIEW

A conventional coal-fired power plant is examined using several approaches in this case study. A detailed exergy analysis of the plant and its components and subsystems is presented, highlighting the insights obtained with exergy analysis. An EXCEM analysis is presented for the plant, including an environmental assessment focusing on the contributions of exergy. It is also shown that, although energy and exergy are dependent on the intensive properties of the reference environment, the main results for coal-fired electricity generation are not strongly sensitive to reasonable variations in these properties. The case study demonstrates the enhanced understanding and benefits realized with exergy and exergy-based environmental and ecological methods, and how such assessments inform technical and environmental improvements.

A conventional coal-fired power plant is considered as a case study. Three analysis approaches that utilize exergy are applied: 1) a detailed exergy analysis of the overall plant and its components and subsystems, 2) an EXCEM analysis including an assessment of the environmental impact of the plant, focusing on exergy aspects, and 3) an examination of the sensitivity of the main results of energy- and exergy-related analyses of the plant to reasonable variations in reference-environment properties.

20.1. EXERGY ANALYSIS

In the first part of this case study, an exergy analysis is performed of a typical coal-fired power plant to demonstrate how exergy analysis improves understanding of its thermodynamic performance relative to energy analysis, and identifies areas with significant potential for improvement.

20.1.1. Process Description and Data

We consider the Nanticoke Generating Station, a typical coal-fired power plant with eight units located in Ontario, Canada, that commenced operating in 1981 under the provincial utility, Ontario Power Generation (formerly Ontario Hydro) (Ontario Hydro, 1996). Each unit has a net electrical output of approximately 500 MW. The main process data are listed in Table 20.1. A flow diagram for a single unit is shown in Figure 20.1, with the corresponding symbols identifying the flows are described in Tables 20.2a and 20.2b for material flows, in Table 20.2c for thermal flows and in Table 20.2d for electrical flows. The four main sections of the plant identified in Figure 20.1 operate as follows:

- *Preheating.* The temperature of the feedwater is increased in several heaters and the pressure is increased in several pumps, to design levels for entering the steam generator.
- *Steam generation.* Water is converted to steam. Eight pulverized-coal-fired steam generators each produce 453.6 kg/s steam at 16.89 MPa and 538°C, and 411.3 kg/s of reheat steam at 4.00 MPa and 538°C. Air is supplied to the combustion furnace by two motor-driven forced draft fans, and regenerative air preheating is used. After treatment in an electrostatic precipitator, the flue gas exits through two multi-flued, 198 m-high stacks.
- *Power production.* Steam from the steam generation section passes through a series of turbine generators, attached to a transformer. The turbine generator contains one single-flow high-pressure cylinder, one double-flow intermediate-pressure cylinder and two double-flow low-pressure cylinders. Steam from the high-pressure cylinder is reheated in the combustor, and steam flows for feedwater heating are extracted.
- *Condensation.* The low-pressure turbines exhaust at 5 kPa to the condenser, where the steam is condensed with cooling water from Lake Erie, which is restricted to a specified temperature rise.

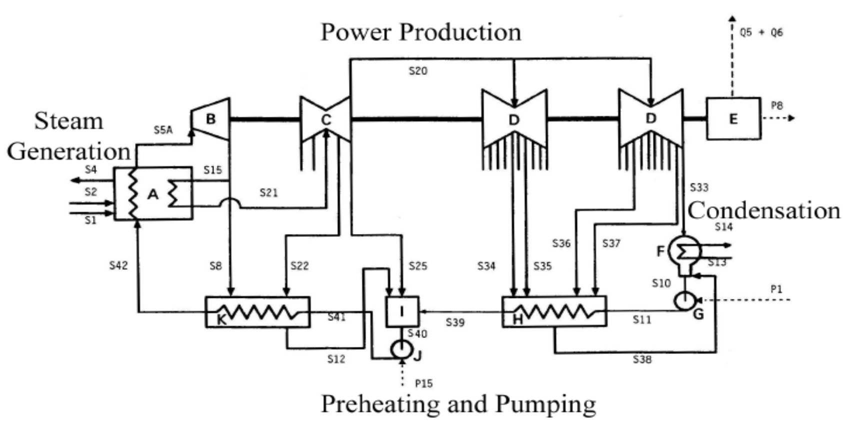

Figure 20.1. Single unit of the coal-fired power plant. For the devices, A: steam generator and reheater, B: high-pressure turbine, C: intermediate-pressure turbine, D: low-pressure turbines, E: generator and transformer, F: condenser, G: hot well pump, H: low-pressure heat exchangers, I: open deaerating heat exchanger, J: boiler feed pump, K: high-pressure heat exchangers. Lines exiting turbines represent flows of extraction steam. Symbols identifying flows are explained in Tables 20.2a-20.2d.

Table 20.1. Primary process data for full-load operation of coal-fired power plant

Data type	Quantity	Flow	Value
Flow rates	Mass (kg/s)	Primary steam	454
		Reheat steam	411
		Coal	47.9
		Cooling water	18,636
	Electricity (MW)	Gross output	524
		Internal use	19
		Net output	505
Intensive properties	Temperature (°C)	Boiler feedwater	253
		Primary steam	538
		Reheat steam	538
		Flue gas	120
		Cooling water rise	8.3
	Pressure (MPa)	Primary steam	16.9
		Reheat steam	4.0
		Condenser	0.005

Table 20.2a. Data for water flows in coal-fired power plant

Flow	Intensive flow properties			Flow rates		
	Temperature (°C)	Pressure (MPa)	Vapor fraction*	Mass (kg/s)	Energy (MW)	Exergy (MW)
S5A	538.00	16.2	1.0	453.59	1585.28	718.74
S8	323.36	3.65	1.0	42.84	135.44	51.81
S10	35.63	0.0045	0.0	367.85	36.52	1.20
S11	35.73	1.00	0.0	367.85	37.09	1.70
S12	188.33	1.21	0.0	58.82	50.28	11.11
S13	15.00	0.101	0.0	18,636	0.00	0.00
S14	23.30	0.101	0.0	18,636	745.95	10.54
S15	323.36	3.65	1.0	410.75	1298.59	496.81
S20	360.50	1.03	1.0	367.85	1211.05	411.16
S21	538.00	4.00	1.0	410.75	1494.16	616.42
S22	423.23	1.72	1.0	15.98	54.54	20.02
S25	360.50	1.03	1.0	26.92	88.64	30.09
S33	35.63	0.0045	0.93	309.62	774.70	54.07
S34	253.22	0.379	1.0	10.47	32.31	9.24
S35	209.93	0.241	1.0	23.88	71.73	18.82
S36	108.32	0.0689	1.0	12.72	35.77	7.12
S37	60.47	0.0345	1.0	11.16	30.40	5.03
S38	55.56	0.0133	0.0	58.23	11.37	0.73
S39	124.86	1.00	0.0	367.85	195.94	30.41
S40	165.86	1.00	0.0	453.59	334.86	66.52
S41	169.28	16.2	0.0	453.59	347.05	77.57
S42	228.24	16.2	0.0	453.59	486.75	131.93

* Vapor fraction is listed as 0 for liquid water and 1 for saturated or superheated vapor.

Table 20.2b. Data for non-water material flows in coal-fired power plant

Flow	State*	Intensive flow properties		Flow rates		
		Temperature (°C)	Pressure (MPa)	Mass (kg/s)	Energy (MW)	Exergy (MW)
S1	Solid	15.00	0.101	41.74	1367.58	1426.73
S2	Gas	15.00	0.101	668.41	0.00	0.00
S3	Gas	1673.59	0.101	710.15	1368.00	982.85
S4	Gas	119.44	0.101	710.15	74.39	62.27

* S1 (fuel) is modeled as pure carbon. By volume, S2 (air) is modeled as 79% N_2 and 21% O_2, and S3 (hypothetical hot product gases for adiabatic combustion, not shown in Figure 20.1) and S4 (combustion gases) as 79% N_2, 6% O_2 and 15% CO_2.

Table 20.2c. Data for thermal energy flows in coal power plant

Flow	Energy flow rate (MW)	Exergy flow rate (MW)
Q5	5.34	0.00
Q6	5.29	0.00

Table 20.2d. Data for electrical energy flows in coal power plant

Flow	Energy flow rate (MW)	Exergy flow rate (MW)
P1	0.57	0.57
P8	523.68	523.68
P15	12.19	12.19

20.1.2. Analysis

Comprehensive energy and exergy analyses are performed. For simplicity, we model coal as graphite and air as 79% nitrogen and 21% oxygen by volume. The turbine isentropic and mechanical efficiencies are 80% and 95%, respectively, and the generator and the transformer efficiencies are both 99%, with heat losses from their surfaces occurring at 15°C. The overall energy efficiency η and exergy efficiency ψ are evaluated as

$$\eta = \text{(Net energy output with electricity)/(Energy input)} \qquad (20.1)$$

$$\psi = \text{(Net exergy output with electricity)/(Exergy input)} \qquad (20.2)$$

Similar efficiency expressions are applied for plant components and sections (except the condenser, since its purpose is not to generate a product, but rather to reject waste heat).

The reference-environment model described in Table 6.1, which simulates the natural environment, is employed in evaluating energy and exergy, but with a temperature set at the approximate mean for the lake cooling water, or 15°C. Corresponding base enthalpy and chemical exergy values reported elsewhere (Rosen and Dincer, 2003a) are used.

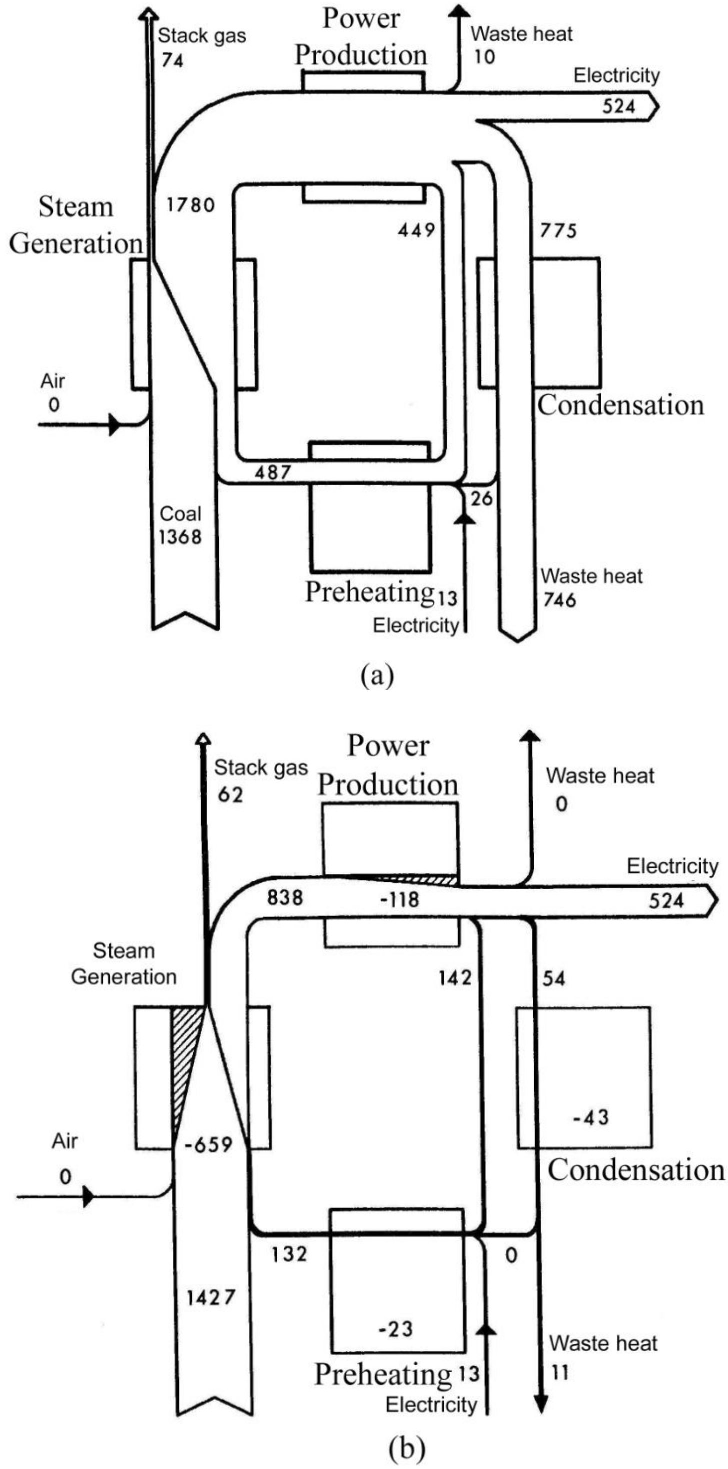

Figure 20.2. Flow rates (in MW) through the four main sections of the coal-fired power plant of a) energy and b) exergy. Thicknesses of flow lines are proportional to the magnitude of the flow rate of the relevant commodity.

20.1.3. Energy and Exergy Flows and Efficiencies

Energy and exergy flow rates are given in Table 20.2 for material, thermal and electrical flows. Device exergy consumptions and their contributions to the overall plant exergy loss are provided in Table 20.3. Figures 20.2a and 20.2b illustrate the net energy and exergy flows and exergy consumptions for the four main process sections. The distribution of outputs (electrical product as well as wastes) is shown for energy in Figure 20.3 and for exergy in Figure 20.4. The latter figure also shows the loss associated with the overall exergy consumption, which is broken down in Figure 20.5.

Table 20.3. Exergy consumption rates for coal-fired power plant

Section	Device	Exergy consumption rate (MW)	% of total exergy loss rate
Steam generation	Steam generator (including combustor)	659.0	71.9
Power production	Turbines	107.9	11.8
	Generator and transformer	10.6	1.2
	Section total	118.5	12.9
Condensation	Condenser	43.1	4.7
Preheating	Heat exchangers	22.2	2.4
	Pumps	1.2	0.1
	Section total	23.4	2.6
Overall		844.0	92.1

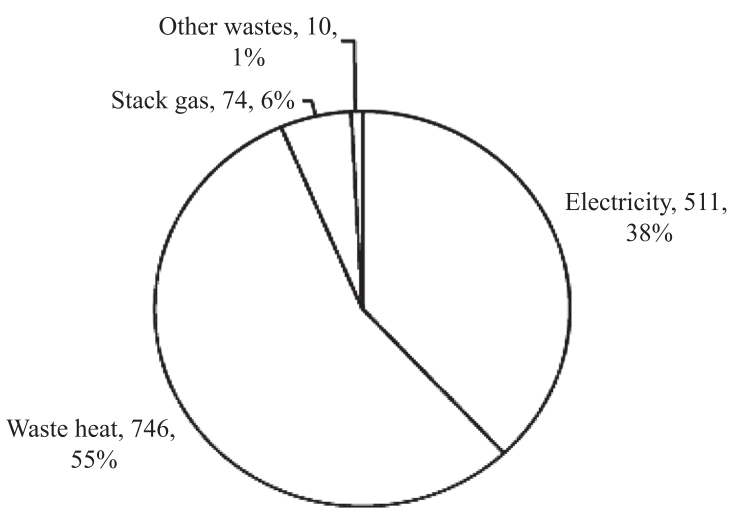

Figure 20.3. Distribution of energy outputs for a coal-fired power plant, showing values in megawatts and as a percentage of the total output.

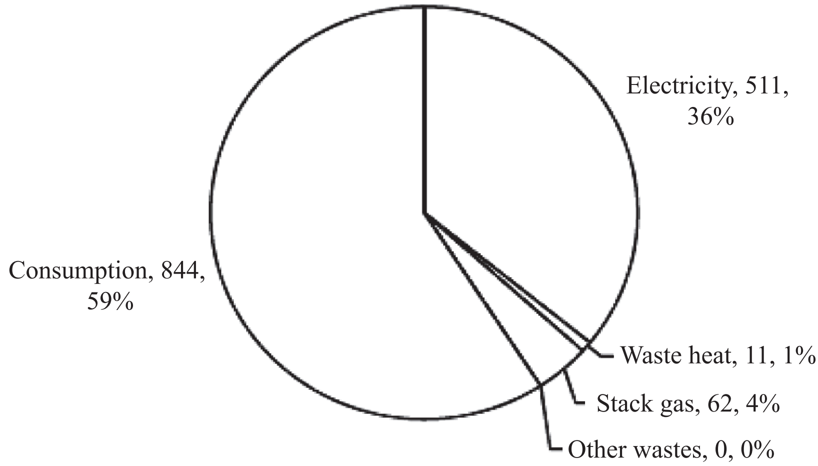

Figure 20.4. Distribution of exergy outputs and exergy consumption for a coal-fired power plant, showing values in megawatts and as a percentage of the total output and consumption.

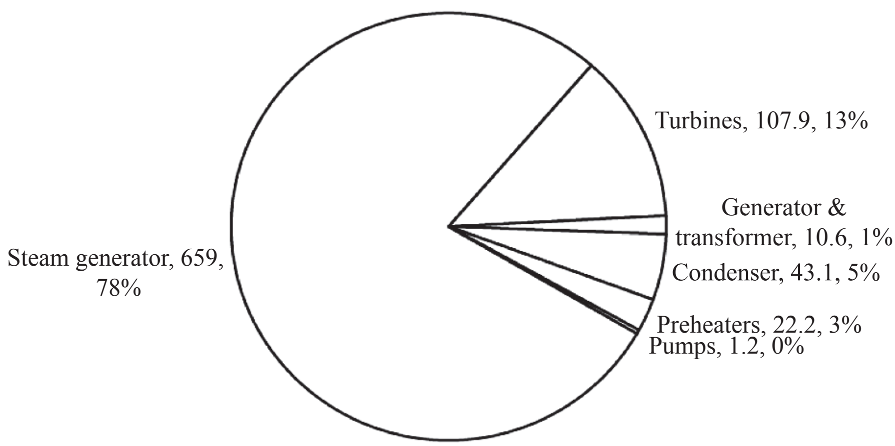

Figure 20.5. Breakdown by device of the exergy consumptions for a coal-fired power plant, showing values in megawatts and as a percentage of the total exergy consumption.

Overall Plant

Overall energy and exergy efficiencies, where coal provides the only input energy or exergy, can be written with Equations (20.1) and (20.2), respectively, as

$$\eta = \frac{(524 - 13)\,\mathrm{MW}}{1368\,\mathrm{MW}}(100\%) = 37\%$$

$$\psi = \frac{(524 - 13)\,\mathrm{MW}}{1427\,\mathrm{MW}}(100\%) = 36\%$$

The difference in efficiencies is minor, and attributable to the specific chemical exergy of coal being slightly greater than its specific base enthalpy.

Plant Sections

In the power production section, energy losses are small (less than 10 MW total), and exergy losses – mainly internal consumptions – are moderately small (around 150 MW).

Energy and exergy efficiencies for the steam generation section, considering the increase in energy or exergy of the water as the product, are

$$\eta = \frac{[(1585 - 847) + (1494 - 1299)]\,\mathrm{MW}}{1368\,\mathrm{MW}}(100\%) = 95\%$$

$$\psi = \frac{[(719 - 132) + (616 - 497)]\,\mathrm{MW}}{1427\,\mathrm{MW}}(100\%) = 49\%$$

The steam generation section is significantly more efficient based on energy than exergy, implying that although 95% of the input energy preheats water, the energy is degraded as it is transferred. Exergy analysis highlights this degradation. Exergy consumptions in the steam generation section are substantial, accounting for 659 MW or 72% of the 916 MW total exergy loss. Of the 659 MW exergy consumption rate in this section, 444 MW is due to combustion and 215 MW to heat transfer.

Energy losses are minor in the preheating section (under 10 MW), as are exergy losses (about 20 MW), which are mainly internal consumptions.

Much energy enters (775 MW) the condensers, of which almost all is rejected, while little exergy enters (54 MW), of which 25% is rejected and 75% is internally consumed. Thus, energy results erroneously suggest that almost all losses in electricity-generation potential are associated with condenser heat rejection, while exergy analyses demonstrate quantitatively and directly that the condensers are responsible for little of these losses (Figures 20.3 through 20.5). This discrepancy arises because condenser heat is rejected at nearly the environment temperature. Exergy results show that the condenser waste is relatively insignificant for the process. The exergy rejected by the condensers is less than 4% of the net exergy produced by the plant, while the energy rejected is approximately 150% of the net energy produced.

Key Insights

The analyses reveal several key insights about coal-fired power generation:

- Energy losses are mainly associated with emissions (i.e., condenser heat rejection), and exergy losses with consumptions (mainly in steam generation).
- Although overall energy and exergy efficiencies are similar, energy analyses do not identify the locations and causes of inefficiencies, while exergy analyses do.
- Since devices with the largest thermodynamic losses have the greatest margins for efficiency improvement, efforts to increase the efficiencies of coal-fired power generation should focus on the combustor. Technologies that generate electricity without combustion (e.g., fuel cells) or utilize heat at high temperatures could increase efficiencies significantly.
- The use of heat rejected by condensers increases the exergy efficiencies by only a few per cent. Cogeneration systems, which produce heat at useful temperatures at the expense of reduced electrical output, can have greater efficiencies than conventional

power generation, but the merit of cogeneration systems should be determined using exergy because energy analyses tend to overstate performance.

20.1.4. Detailed Illustration for Plant Subsystem

To provide a simplified and clear illustration of the application of exergy analysis and the corresponding insights gained, we assess a subsystem of the coal-fired plant. The subsystem includes the low-pressure turbine (device D in Figure 20.1) and the electrical generator and the transformer (together shown as device E in Figure 20.1). A detailed flow diagram for this subsystem is shown in Figure 20.6, with corresponding data described in Table 20.4 for material flows and in Table 20.5 for electrical and thermal flows and work interactions.

Table 20.4. Data for material flows (all H_2O) in subsystem of coal-fired power plant

Flow	Intensive properties			Flow rates		
	Temp. (°C)	Pres. (MPa)	Vapor fraction*	Mass (kg/s)	Energy (MW)	Exergy (MW)
Inlet steam (S20 in Figure 20.1)	360.50	1.03	1.0	367.85	1211.1	411.2
Exhaust steam (S33)	35.63	0.0045	0.93	309.62	774.7	54.1
Extraction steam 4 (S34)	253.22	0.379	1.0	10.47	32.3	9.2
Extraction steam 3 (S35)	209.93	0.241	1.0	23.88	71.7	18.8
Extraction steam 2 (S36)	108.32	0.0689	1.0	12.72	35.8	7.1
Extraction steam 1 (S37)	60.47	0.0345	1.0	11.16	30.4	5.0

* Vapor fraction is listed as 0 for liquids and 1 for saturated or superheated vapors or gases.

Table 20.5. Data for electrical and thermal flows and work interactions in subsystem of coal-fired power plant

Type	Flow/interaction	Energy flow rate (MW)	Exergy flow rate (MW)
Thermal	Waste heat (turbine, mechanical efficiency)	0.0	8.4
	Waste heat (generator)	2.6	0.2
	Waste heat (transformer)	2.6	0.2
Electrical	Electricity (exiting generator)	255.2	255.2
	Electricity (exiting transformer)	252.6	252.6
Work	Shaft work (turbine)	257.8	257.8

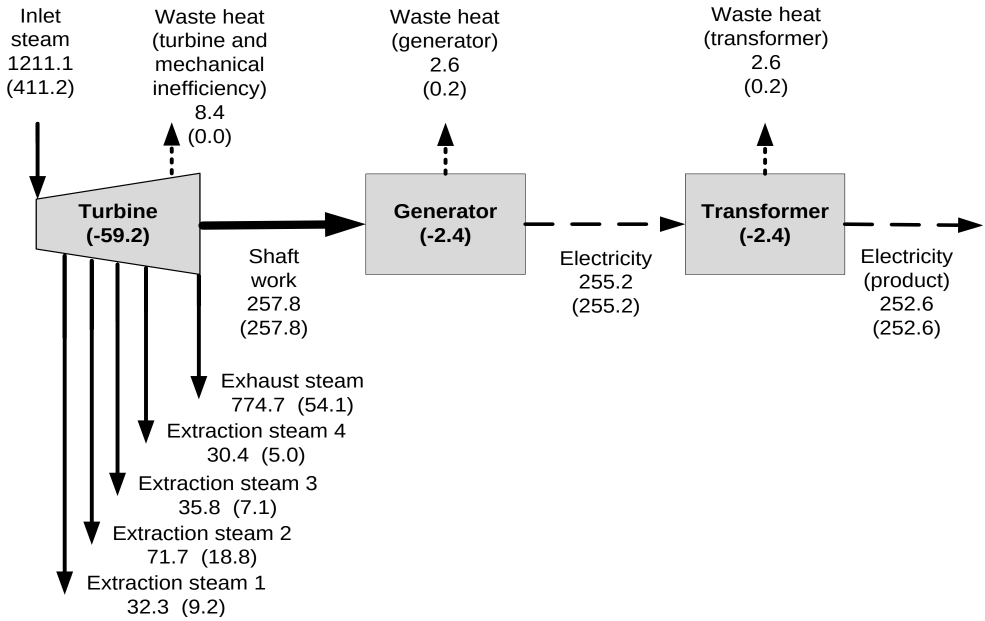

Figure 20.6. Subsystem of the coal-fired power plant, and its energy and exergy flow diagram. Flows are denoted by dashed lines for thermal energy, dotted lines for electrical energy, thin solid lines for material and thick solid lines for work transfers. Indicated are flow rates of energy (values not in parentheses) and exergy (positive values in parentheses) for flows and interactions, and exergy consumption rates (negative values in parentheses) for devices. All values are units of MW.

Assumptions

Simplifications and assumptions employed in the analysis, and relevant data, follow:

- The turbine isentropic efficiency η_{isen} is 80%, the turbine mechanical efficiency η_{mech} 95%, the generator efficiency η_{gen} 99%, and the transformer efficiency η_{tran} 99%.
- The "surface" from which heat losses are emitted is at a temperature of 40°C for the generator and transformer, and 15°C (the reference-environment temperature T_o) for the turbine (including the turbine rotor shaft). The "surface" temperatures are not actual device surface temperatures, but rather are the temperatures of the control volumes taken to be surrounding each device. These control volumes can be arbitrarily located and can include some of the air surrounding each device.

Flows

An energy/exergy flow diagram for the subsystem of the coal-fired plant considered is shown in Figure 20.6. Only the portion of the work and electricity outputs due to the low-pressure turbine are shown here, because only the low-pressure turbine is considered in this analysis. Thus, the shaft work exiting the turbine in Figure 20.6 only represents the output of the low-pressure turbine. In reality, more work is produced by the plant since the turbine shaft of the low-pressure turbine is also linked to high- and intermediate-pressure turbines.

It is seen in Figure 20.6 that the energy entering the system via steam is much greater than the exergy entering, and that the energy associated with each of the steam extraction flows and the turbine exhaust steam is much greater than the corresponding exergy. The main exergy loss is associated with the turbine and is in the form of an exergy consumption, which is due to the irreversibilities of the expansion process in the turbine. It is also observed that the exergy and energy rates are the same for work and electricity, while the energy and exergy rates differ for material and thermal energy flows. Here, the exergy rates of material and thermal flows are less than the energy rates, but this is not the case in general.

Note that if the extraction steam flows were eliminated, the work generated by the turbine would increase. However, the heat input to the overall plant would simultaneously have to increase at a higher proportion, resulting in a reduction in the overall energy and efficiencies of the power plant. On an energy basis, the amount of heat removed by extraction steam flows is large, but these values are all correspondingly much smaller on exergy bases.

Table 20.6. Energy and exergy balances for the system considered

Flow/loss type	Flow/loss	Energy		Exergy	
		MW	% of input energy	MW	% of input exergy
Inputs	Inlet steam	1211.1	100.0	411.2	100.0
Outputs and losses	Output products (electricity, extraction steam)	422.8	34.9*	292.7	71.1**
	Output losses (exhaust steam, waste heat)	788.3	65.1	54.5	13.3
	Internal losses (turbine, shaft, generator, transformer)	–	–	64.0	15.6
	Total outputs and losses	1211.1	100.0	411.2	100.0

* This value is the overall energy efficiency of the subsystem considered.

** This value is the overall exergy efficiency of the subsystem considered.

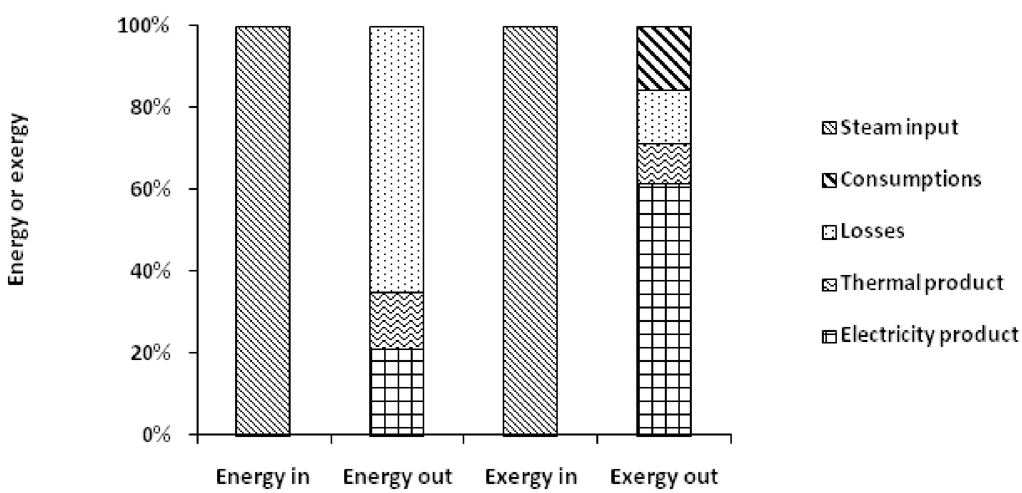

Figure 20.7. Normalized balances on the basis of energy (left two bars) and exergy (right two bars). The left bar of each pair of represents inputs, and the right bar outputs (and, for exergy, consumptions).

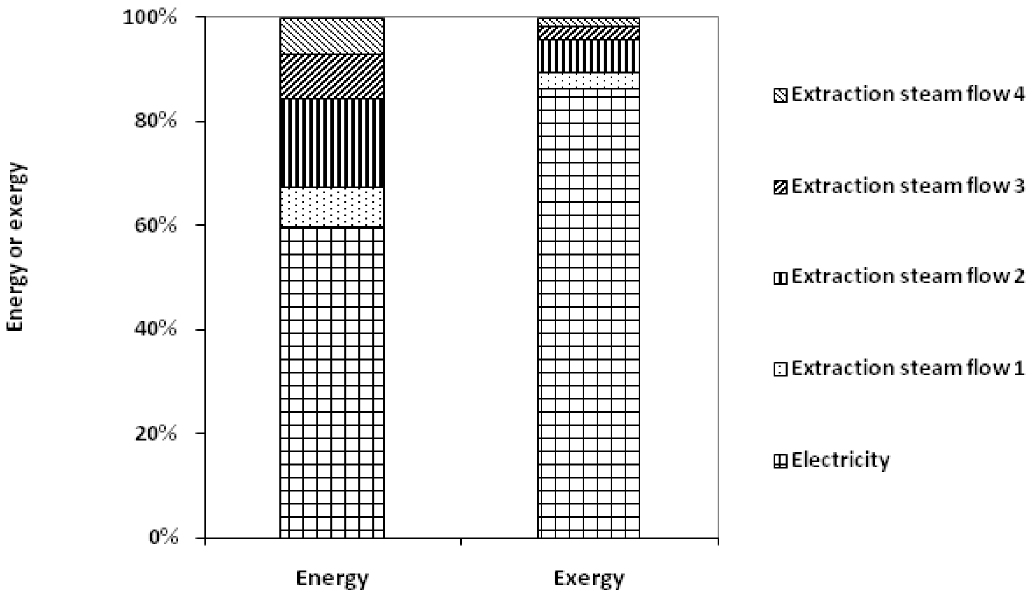

Figure 20.8. Breakdown of products on the basis of energy (left) and exergy (right).

Balances

Energy and exergy balances for the system considered are presented in Table 20.6, in absolute and relative units. Again, it is pointed out that only the portion of the work and electricity outputs due to the low-pressure turbine are shown here. The observations noted via the flow diagram in Figure 20.6 are reinforced by Table 20.6, but in a different manner. In particular, the differences in the energy and exergy losses are highlighted.

Normalized energy and exergy balances are presented in Figure 20.7. The differences in the relative magnitude of the energy and exergy of the products and of the losses are emphasized. The electrical product is a much greater proportion of the outputs and losses based on exergy rather than energy. Exergy losses include consumptions while energy losses do not. The main exergy losses are associated with consumptions while the main energy losses are associated with waste emissions.

Breakdown of Products

Breakdowns of the products (electrical and thermal) for the system considered are presented in Figure 20.8, on both energy and exergy bases. The exergy results in this figure emphasizes how electricity is much more valuable than heat at finite temperatures.

Breakdown of Losses

A breakdown is shown in Table 20.7 of the energy and exergy losses for the system, in absolute and relative units. The losses are divided into external (waste emissions) and internal (consumptions) parts. External losses of both energy and exergy occur, but internal losses are only possible for exergy and these are the exergy consumptions, which are often referred to as exergy destructions. Internal losses are not possible for energy because it is conserved.

Table 20.7. Breakdown of energy and exergy losses for the system considered

Loss type	Loss source	Energy loss rate		Exergy loss rate	
		MW	% of input energy	MW	% of input exergy
External	Exhaust steam to condenser	774.7	98.3	54.1	45.7
	Waste heat from turbine and shaft	8.4	1.1	0.0	0.0
	Waste heat from generator	2.6	0.3	0.2	0.2
	Waste heat from transformer	2.6	0.3	0.2	0.2
	Subtotal	788.3	100.0	54.5	46.0
Internal	Turbine	-	-	59.2	50.0
	Generator	-	-	2.4	2.0
	Transformer	-	-	2.4	2.0
	Subtotal	-	-	64.0	54.0
All	External and internal total	788.3	100.0	118.5	100.0

Table 20.8. Component and overall efficiencies for the system considered

Device	Products	Inputs	Efficiency (%)	
			Energy, η	Exergy, ψ
Turbine (overall)	Shaft work Extraction steam	Low-pres. steam	35.3	72.4
Turbine (work only)	Shaft work	Low-pres. steam	21.3	62.7
Generator	Electricity	Shaft work	99.0	99.0
Transformer	Electricity	Electricity	99.0	99.0
Overall	Electricity Extraction steam	Low-pres. steam	34.9	71.1

On energy and exergy bases, the losses differ significantly. The energy loss is totally due to waste emissions, but for exergy losses the contributions of exergy consumption and waste exergy emission are both significant, at 54% and 46% of the total exergy loss, respectively. The main exergy loss is associated with internal consumptions, predominantly in the turbine, where 50% of the total exergy loss occurs. The second highest exergy loss is associated with the low-pressure turbine exhaust steam passing to the condenser (which is responsible for 46% of the total exergy loss).

A significant observation in Table 20.7 is that the exergy loss rate (788.3 MW) is over six times the exergy loss rate (118.5 MW). This is typical of successful industrial systems which tend not to release significant quantities of exergy with wastes, usually because the usefulness or quality of these flows makes them valuable and worth recovering. There is no corresponding logical behavior observed in general for energy losses, which can be larger or smaller and do not generally reflect quality or value.

Efficiencies

Component and overall efficiencies for the subsystem considered, evaluated using Equations (20.1) and (20.2), are presented in Table 20.8 on energy and exergy bases. For clarity, the product outputs and inputs for each device are given. Two efficiencies are listed for the turbine: one considering electricity and useful heat as the “product” and one considering only electricity as the product. Because the exergy of heat is less than its energy, the energy efficiencies vary greatly by an absolute increment of 14% (i.e., the exergy efficiency with heat included as a product is 65.7% greater than without), but the exergy efficiency varies by less (only 9.7% in absolute terms), or the exergy efficiency with heat considered as a product is only 15.5% greater than without. The overall efficiency in Table 20.8 considers electricity and useful heat as products.

The efficiencies for the turbine are both much less than those of the generator or transformer. The overall efficiencies are similar to the turbine (overall) efficiency because the efficiencies of the generator and transformer are very high. The exergy efficiency of the turbine is significantly greater than the energy efficiency because the turbine converts a high proportion of the “work potential” (i.e., exergy) in the incoming steam to work, but a much lower proportion of the energy with incoming steam, which is not a measure of its “work potential.” Thus exergy analysis indicates that the turbine is much more efficient than does energy analysis, reflecting a meaningful and useful efficiency for the device.

The extraction steam flows represent an internal use of cogeneration in the coal-fired power plant. The efficiencies in Table 20.8 change if this use of cogeneration is expanded to recover the exhaust heat flow from the low-pressure turbine rather than sending it to the condenser where its heat is rejected to the lake. Although the temperature of the low-pressure turbine exhaust steam is relatively low (36ºC), such a use of expanded cogeneration could find some applications (e.g., aquaculture). If the efficiencies obtained here are re-evaluated, it is seen that cogeneration has a small effect on the exergy efficiency, but a large effect on the energy efficiency. This observation suggests that exergy efficiencies realistically assess the benefits of cogeneration, while energy efficiencies tend to exaggerate the benefits.

Insights

Several illuminating insights are attained about the subsystem of the coal-fired power generation plant considered:

- Energy losses are mainly in waste emissions (low-pressure exhaust steam), and exergy losses in consumptions (mainly with turbine expansion).
- The energy and exergy efficiencies of the subsystem and its components differ. Exergy values identify the locations and causes of inefficiencies and margins for improvements.
- Based on exergy losses, efforts to increase the efficiency of the subsystem should focus on the turbine. Significant improvements may be achievable through alternative expanders and technologies that generate shaft work from steam more efficiently or turbine-efficiency improvement measures. But the use of the heat of the turbine exhaust steam, which is rejected by the condensers, only increases the exergy efficiency of the subsystem slightly.

If a use for the low-pressure turbine exhaust steam is found, it becomes a by-product and the energy efficiency increases significantly (while the energy loss rate decreases to 13.6 MW from 788.3 MW). The exergy efficiency is much less affected, with the exergy loss rate decreasing to 64.4 MW from 118.5 MW.

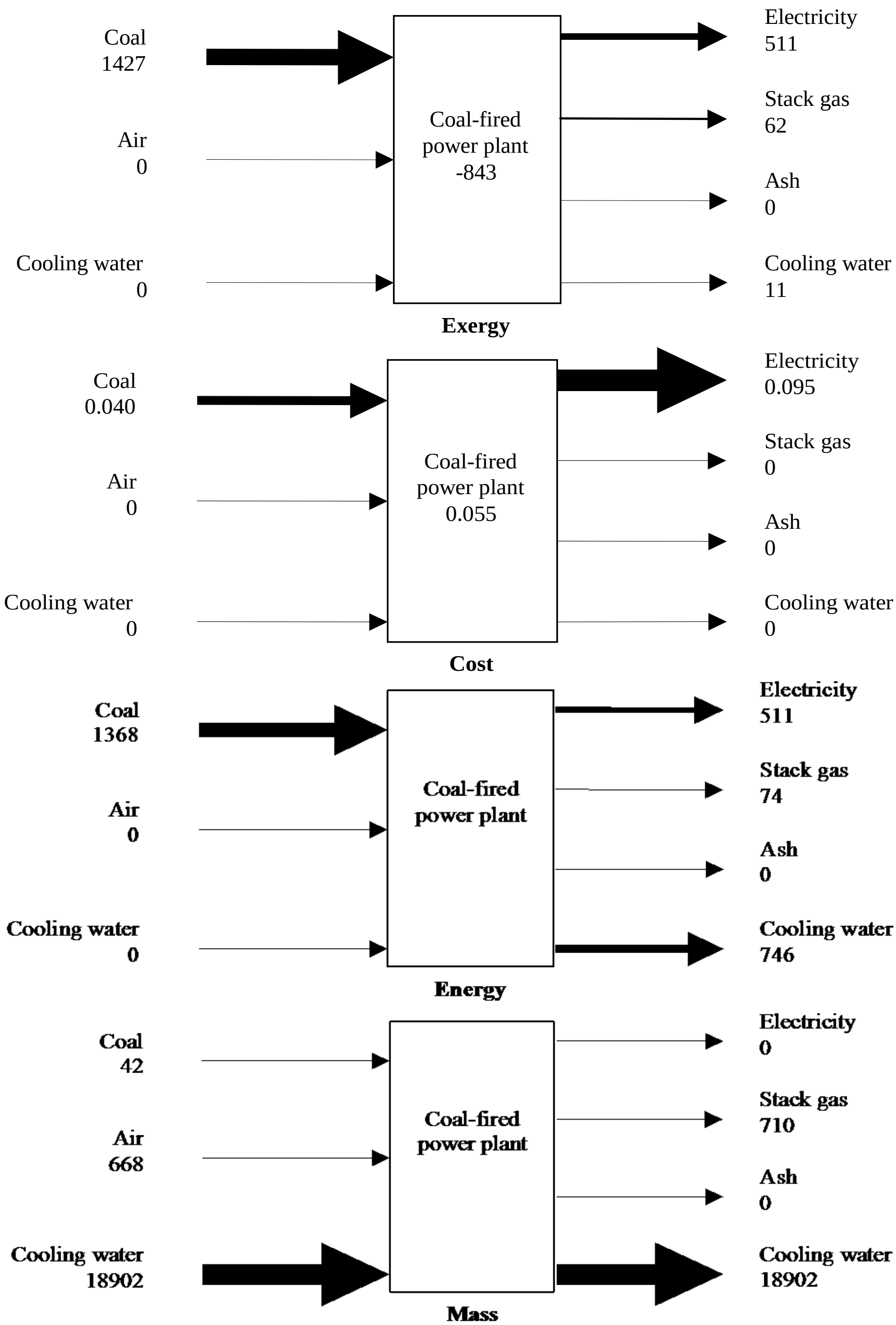

Figure 20.9. Balances of exergy, cost, energy and mass for a coal-fired power plant. The exergy balance shows flow rates and consumption rate (negative value in plant) of exergy (in MW). The cost balance shows flow rates and creation rate (value in plant) of cost (Canadian $/kWh, adjusted to 2007 Canadian dollars as explained in Rosen (2011)). The energy balance shows energy flow rates (in MW) and the mass balance shows mass flow rates (in kg/s). In all balances, thicknesses of flow lines are proportional to the magnitude of the flow rate of the corresponding commodity.

This is analogous to converting the entire plant to cogeneration (noting that thermal energy in extraction flows is already used for productive purposes of preheating, in essence acting as internal cogeneration). But this idea is dependent on the temperature of the low-pressure turbine exhaust being large enough to have a use.

The results also have important economic repercussions. It can be seen in Figure 20.8 that if the costs of products are weighted on the basis of energy, much different results are obtained than if they are weighted on the basis of exergy. Specifically, it is noted that:

- Weighting by energy overvalues heat and undervalues electricity.
- Weighting by exergy is more realistic and emulates what is observed in practice more closely (implying an exergy weighting yields more realistic costs or prices).

20.2. EXCEM ANALYSIS AND ENVIRONMENTAL IMPACT ASSESSMENT

An EXCEM analysis is presented for the coal-fired power plant, including an environmental impact assessment focusing on the contributions of exergy to understanding.

20.2.1. EXCEM Analysis

The coal-fired power plant considered in Section 20.1 is examined using EXCEM analysis, and Figure 20.9 illustrates the results. In this figure, exhaust cooling water and stack gas are treated as wastes, and input and generation costs are allocated to the product electricity. The EXCEM results highlight where resources are being consumed, losses are occurring and wastes are being emitted, considering exergy, energy and mass measures, and tracking costs. Thus the EXCEM results help describe potential environmental and ecological impacts, and assist the development of cost-effective measures to avoid such impacts.

20.2.2. Environmental Impact Assessment

As a continuation of the EXCEM analysis in the previous section, the exergy-environment relations described in Section 7.2 are illustrated for the coal-fired generating station.

First, order and resource degradation occur during the exergy-consuming conversion of coal to less ordered combustion gases. Although some resource degradation is unavoidable for a real process, increased exergy efficiency can reduce the degradation. In the extreme, if the process in the example were made thermodynamically ideal (a hypothetical supposition) by increasing the exergy efficiency from 37% to 100%, coal use and the related emissions would each decrease by over 60%. These insights are provided by exergy, but not energy.

Second, the waste emissions contain exergy, indicating simultaneously that they pose a risk to the environment but are a source of useful energy. Two main wastes are emitted:

- *Stack gas*: Societal concern regarding emissions of harmful chemical constituents suggests that the potential for impact of these emissions is recognized, but not from the perspective provided by exergy. Also, since exergy restricted in a system represents a resource while the unrestricted emission of exergy to the environment represents a possible driving potential for environmental damage, two benefits may result if the exhaust gas is restricted rather than emitted to the environment: environmental damage is potentially avoided, and the restricted waste becomes a potentially valuable source of exergy.
- *Waste heat*: Waste exergy emitted with waste heat to the atmosphere and lake represents a potential to impact the environment. Concern exists regarding thermal pollution in bodies of water, and exergy-based insights into environmental-impact potential of such phenomena could improve our understanding.

Third, chaos is created via the degradations described in the first two points (i.e., resource degradation as coal is used and surroundings degradation due to emissions). The degradation of fuel is apparent since the process products have less exergy than the inputs. The potential degradation of the environment due to waste emission exists if the emissions to the environment occur without constraint.

Note that the results obtained in the subsystem analysis in Section 20.1.4 also provide useful information on environmental impact. The waste energy emission to the environment is seen in Figure 20.7 to be large. But this large magnitude is somewhat misleading in terms of potential for environmental impact of this waste, because the release is in – or nearly in – equilibrium with the environment, since the heat release is almost at the reference-environment temperature T_o. The exergy results reflect this reality, as there is little exergy in the waste heat emissions.

This case study clearly demonstrates that exergy losses, whether in the form of exergy destruction or waste emissions, relate to environment impact. Exergy destruction, in particular, provides a significant criterion for assessing the depletion of natural resources. Thus, exergy analysis can help reduce resource use by indicating where the work potential or exergy of natural resources is lost. Furthermore, the exergy in a flow can only be entirely converted to products in a reversible process, i.e., one where exergy is neither destroyed nor emitted as waste. A reversible process is a theoretical ideal which we can seek but never realize. Real processes, which are irreversible, have exergy destructions and waste exergy emissions. Effort is often expended on reducing resource exergy destructions and waste exergy emissions, sometimes by converting them to by-products.

20.3. SENSITIVITIES OF ENERGY AND EXERGY ANALYSES TO VARIATIONS IN REFERENCE ENVIRONMENT PROPERTIES

The sensitivity to reasonable variations in reference environment properties of the main results of energy and exergy analyses of the coal-fired power plant is demonstrated in this section. The base case analysis of the coal-fired generating station in the previous section used the reference-environment model in Table 6.1, but with a reference-environment temperature of 15°C based on the approximate mean temperature of the lake cooling water.

The main analysis results are re-evaluated via computer simulation in this section for two alternate reference-environment temperatures: 5°C and 25°C. For each alternate value of T_o, two sets of energy and exergy values are obtained:

- The simulation remains unchanged from that for the base case when the reference-environment temperature T_o is changed.
- The simulation is modified from that for the base case when T_o is changed, by setting the temperatures of streams entering from the environment (S1, S2, S13, S16, S18) to the appropriate value of T_o. Note that only preliminary modifications to plant components are considered, even though an optimal new design for the plant would be developed if T_o were altered in reality.

Selected energy and exergy efficiencies and flow rates are listed in Table 20.9 for the base case value and two alternate values of the reference-environment temperature, for the altered and unaltered simulations.

Table 20.9. Values of selected exergy and energy parameters of the coal-fired power plant for several values of the reference-environment temperature T_o

Parameter	Base case	Unaltered simulation		Altered simulation	
	T_o=15°C	T_o=5°C	T_o=25°C	T_o=5°C	T_o=25°C
Exergy efficiency (%)					
Overall plant	35.8	35.8	35.8	35.6	36.0
Steam generators	49.5	50.9	48.1	50.7	48.3
Energy efficiency (%)					
Overall plant	37.4	37.4	37.4	37.2	37.6
Steam generators	94.7	94.6	94.6	94.1	95.1
*Exergy flow rates (MW)**					
Coal (S1)	1427	1427	1427	1435	1419
Stack gas (S4)	62.3	64.6	60.2	64.9	59.9
Superheater steam (S5A)	719	749	689	749	689
Reheat steam (S21)	616	647	586	647	586
LP turbine exhaust steam (S33)	54	79	29	79	29
Preheated feedwater (S42)	132	145	120	145	120
Gross electrical power (P8)	524	524	524	524	524
*Energy flow rates (MW)**					
Coal (S1)	1368	1367	1368	1368	1360
Stack gas (S4)	74.4	81.4	67.3	81.9	67.0
Superheater steam (S5A)	1585	1607	1563	1607	1563
Reheat steam (S21)	1494	1514	1474	1514	1474
LP turbine exhaust steam (S33)	775	790	760	790	760
Preheated feedwater (S42)	487	509	465	509	465
Gross electrical power (P8)	524	524	524	524	524

* Flow numbers in parentheses correspond to those shown in Figure 20.1.

The efficiencies for the overall plant and for the steam generator are listed in Table 20.9, and observed to be only slightly sensitive to variations in reference-environment temperature for the altered and unaltered simulations. The variations for most energy and exergy flow rates are less than 10%. The gross electrical power does not change in any of the cases since the energy and exergy of electricity are the same, and not dependent on the reference environment properties. The exergy values are relatively insensitive to the composition of the reference environment for the material flows of water compared to flows of coal and stack gas.

For the unaltered simulations, the variations in the reference-environment temperature T_o cause the absolute values of the component irreversibilities to change, but leave the relative component irreversibilities (as a fraction of the total plant irreversibility) unchanged. For the altered simulations, the irreversibilities are redistributed among the various components, as both the absolute and relative component irreversibilities change.

It is evident from the sensitivity analyses that the main results for the base case analysis are not significantly affected by the variations in T_o considered here. Note that although the variations in T_o considered do not significantly affect the overall results, these variations are important in determining the optimal operating point for a given plant design.

20.4. Closing Remarks

A case study is considered of a conventional coal-fired power plant. The exergy analysis of the plant and its components provides illuminating insights, e.g., the combustor has the greatest margin for true thermodynamic improvement of the plant's performance and the use of condenser waste heat increases plant exergy efficiencies only marginally. The detailed analysis of a plant subsystem consisting of three devices (the low-pressure turbine, the electrical generator and the electrical transformer) further illustrates the exergy approach. The EXCEM analysis, including an analysis of the plant from the perspective of its environmental impact as described with an exergy approach, demonstrates the enhanced understanding realized with exergy analysis and exergy-based environmental and ecological methods, the potentials they provide for technical and environmental improvements and, more generally, the benefits of considering exergy in environmental and ecological assessments. It is also demonstrated that, although energy and exergy values are dependent on the intensive properties of the reference environment, the main results of energy and exergy analyses, as well as environmental analyses based on exergy, for coal-fired electricity generation are usually not significantly sensitive to reasonable variations in these properties.

Chapter 21

SMOKESTACK OPERATIONS

OVERVIEW

The exergy distribution characteristics of pollutants emitted from a smokestack provide a means by which exergy can potentially provide a pollution assessment standard that captures in one or few measures many of the characteristics of pollutants emitted from combustion smokestacks, making it easier to identify the magnitudes and locations of the most significant environment and ecological impacts and hazards. An exergy-based environmental impact measure based on tolerance limits is a useful extension that may provide the basis for an exergy-based standard for environmental acceptability.

The exergy distribution characteristics of pollutants emitted from a smokestack are assessed to demonstrate the potential of exergy to provide a pollution assessment standard. Then, the work is extended to include tolerance limits to develop another exergy-based environmental impact measure.

21.1. EXERGY-BASED AIR POLLUTION LEVELS FROM A SMOKESTACK

Exergy has the potential to be incorporated in measures to assess the properties and potential impacts of pollutants. This includes emissions from large smokestacks, such as those for large coal-fired boilers and power plants. A corresponding method was developed of the exergy distribution characteristics of pollutants emitted from a smokestack, such as SO_2, NO and CO_2, and heat, as well as combined emissions (Rosen and Ao, 2008a, 2008b). The method demonstrates how exergy can potentially provide a pollution assessment standard that captures in one measure, or several measures, many of the characteristics of pollutants emitted from combustion systems, making it easier to identify the magnitudes and locations of the most significant environmental impacts and hazards.

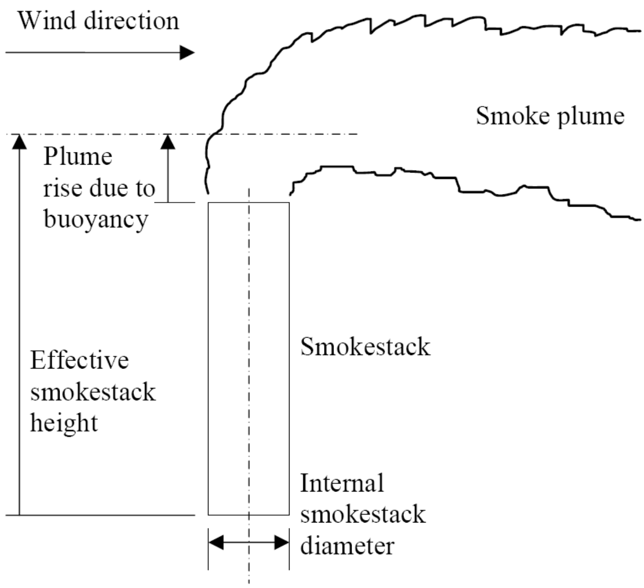

Figure 21.1. Model of smoke plume emission from a smokestack in windy conditions.

21.1.1. Methodology

In this method, spatial variations are established of the temperature of the stack gas, the concentrations of the pollutants (CO_2, SO_2, NO), and the exergy of the pollutants emitted from the source. Then, the distribution characteristics are determined along the average wind direction of temperature and chemical pollutant concentrations s separately and combined at different heights, and corresponding exergy values are determined.

A smokestack and the plume emitted from it are modeled as in Figure 21.1. The smoke plume rises due to buoyancy forces and velocity after being emitted, and is subsequently blown by the wind in a downwind direction. As described by Rosen and Ao (2008a, 2008b), the Pasquill-Gifford model, which is a simplified conventional Gauss diffusion smoke model, is utilized to model the spatial distribution of the pollutant concentration, and the Jaluria density model is used to determine the temperature distribution of the plume.

The spatial distributions are ascertained of the concentrations of gaseous pollutants, along the main direction of the local wind and in other directions, of the temperature of the stack gas, and of the thermal exergy, chemical exergy and overall exergy of the stack gas. These data are determined at various heights, including the stack height or the effective stack height (the plume emission height accounting for buoyancy effects as the plume exits from the stack and rises), and near or at ground level.

21.1.2. Illustration

An illustration of the method is given in which we determine whether the distribution properties as well as the main pollutants and pollution locations are similar and more easily identified with exergy. A hypothetical coal furnace is considered having a stack height of 50 m and an internal exit diameter of 2 m. The furnace burns coal with a typical composition (77% C, 5% H and 18% others by mass) at a rate of 60 t/h. Smoke at 200°C exits the stack at a rate of 250,000 m^3/h. The local average wind speed is 3 m/s at ground level and the vertical speed at which smoke exits the stack is 8 m/s, and the mean ambient air temperature is 25°C.

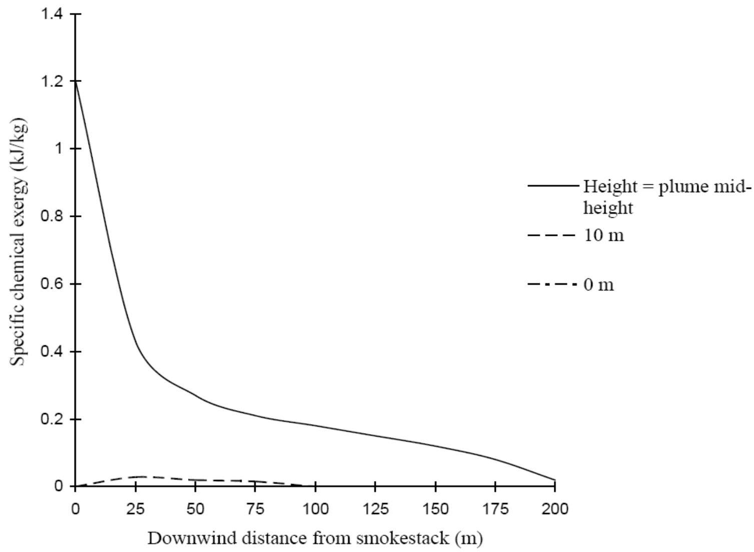

Figure 21.2. Variation of specific chemical exergy with distance downwind of emission point for several heights. The curve for a height of 0 m overlaps with the horizontal axis.

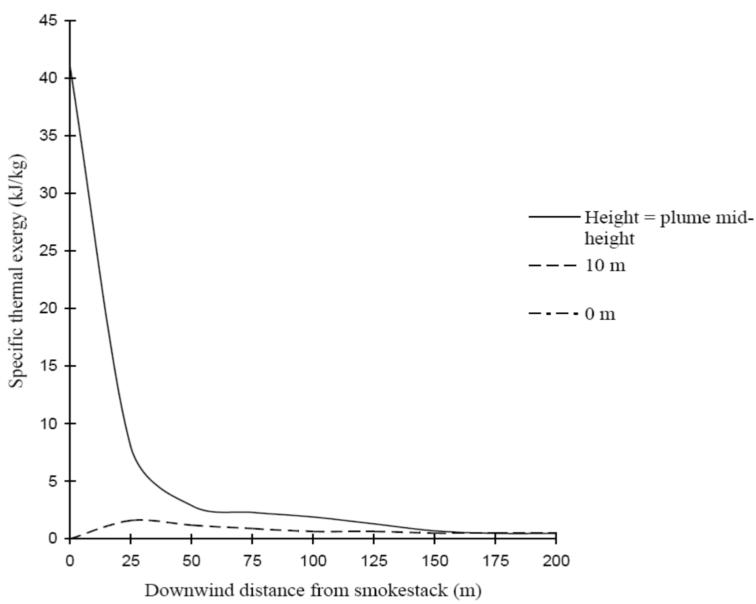

Figure 21.3. Variation of specific thermal exergy with distance downwind of emission point for several heights. The curve for a height of 0 m overlaps with the horizontal axis.

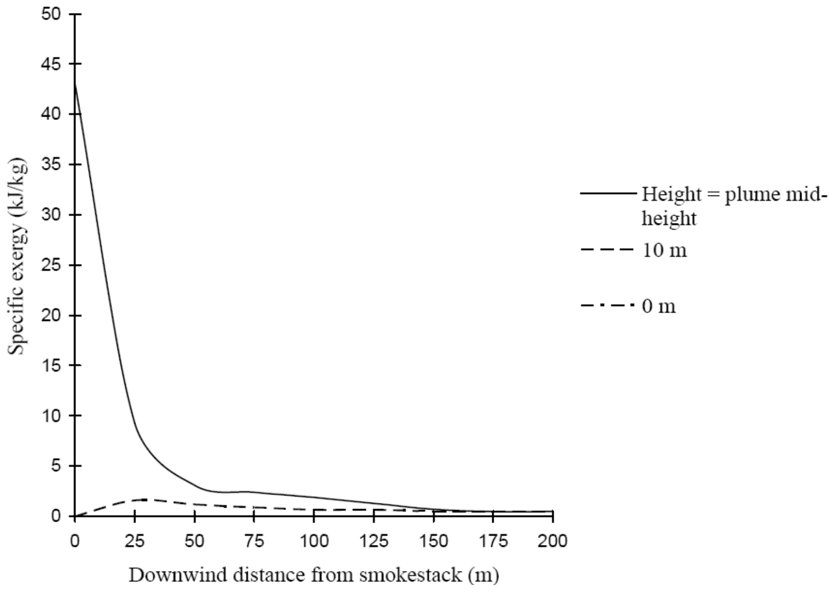

Figure 21.4. Variation of specific exergy with distance downwind of emission point for several heights. The curve for a height of 0 m overlaps with the horizontal axis.

Several spatial distributions are illustrated at several heights along the direction of the local wind. The spatial distributions of the specific chemical exergy for all the chemical constituents of the stack gas (including CO_2, SO_2 and NO) are shown in Figure 21.2. The spatial distributions of the specific thermal exergy of the stack gas are presented in Figure 21.3. The spatial distributions of the total exergy, which combines the variations for the thermal and chemical exergy of the stack gas, are shown in Figure 21.4.

The results exhibit many interesting features. The exergy distribution of the plume at heights near the stack exit is markedly different than the distribution near or on the ground. At the effective stack height, the chemical exergy variations exhibit characteristics similar to those for the corresponding concentration variations. The thermal exergy shown in Figure 21.3 is significant within a sphere of 100 meters at the effective stack height, so impacts due to thermal pollution should be considered within this range. The variations at lower heights are of a lower magnitude, but can be of greater significance due to the proximity to people, animals and plants on the ground. The results suggest that reliance on rapid dispersion and diffusion of pollutants into the atmosphere is not a highly effective means of controlling pollution. Depending on the criteria considered for pollution prevention, alternative methods of pollution control, such as capturing pollutants prior to emission, may be more effective.

The method provides a way of assessing using exergy the air pollution levels from a smokestack, and can provide indicators of potential environmental harm, by focusing on the magnitudes of exergy and its components, in surrounding regions.

21.2. Environmental Impact Measures Based on Exergy and Tolerances

By extending the model developed by Rosen and Ao (2008a, 2008b) to include tolerance limits, another exergy-based environmental impact measure is developed. People, animals, plants and ecosystems have limits to external changes before they become altered. For example, concentration limits of 0.8 mg/m^3 for SO_2 and 0.28 mg/m^3 for NO_2 correspond to the levels at which healthy people fall ill (Hao and Ma, 2003). The exergy of each pollutant in smokestack emissions at its specified tolerance limit can be used as a measure its potential environmental impact and as an exergy-based standard for environmental acceptability.

For the illustration of the plume from a coal smokestack considered in the previous section, this method provides additional insights:

- Although the chemical exergy of CO_2 is about 100 times that of SO_2 and NO, the pollution levels of SO_2 and NO are much higher than that of CO_2. This observation may imply that impacts from SO_2 and NO to the environment are potentially more significant, based on tolerance limits.
- The total pollution level of the combined pollutants in the plume near the ground demonstrates that ground-level environmental impacts from a coal-fired combustor begin around 10 meters from the smokestack and end around 20,000 meters downwind. Such information can help efforts to predict and control air pollution.

It is recognized that the method discussed here has a degree of subjectivity, as more than one tolerance limit can often be developed for a given pollutant. For example, the tolerance limit described earlier in this section for CO_2 could be based on human toxicity levels or on an annual minimum allowable atmospheric greenhouse warming impact. Different tolerance limits yield different allowable pollution levels. Also, lowering the tolerance limit of people, animals and plants to a pollutant causes the value of the pollution level associated with that pollutant for a given situation to increase, indicating a greater potential impact of the pollutant on the environment. Thus, the choice made for the tolerance limit of a pollutant exergy affects significantly the ensuing results, so careful consideration must be given to the selection process. For this assessment methodology to be widely adopted, realistic and representative exergy-based tolerance limits for a range of pollutants must be determined.

Table 21.1. Normalized emissions (in mg/m^3 fuel) for two aircraft engines at several power settings

Aircraft engine	Power setting	Hydrocarbons (total)	NO_x	NO_2	CO_2
JT8D-219	Idle	2.1	3.8	0	0.55
JT8D-219	Maximum	3.6	32	18	1.3
APU	Normal	7.2	48	40	13.5

Sources: Winther et al. (2006) and Turgut and Rosen (2012).

21.3. Extension to Other Emissions

The exergy distribution characteristics of pollutants emitted from a smokestack, and the corresponding exergy-based approach to emission tolerances, can be extended to other gaseous emissions from combustion.

For instance, consider the emissions to the atmosphere from aircraft, for which several experimental values are listed in Table 21.1 for various engine power settings. When an aircraft is near an airport, as is the case during ground idle, takeoff and landing, the emissions can be considered to be somewhat like those from a fixed smokestack, and assessed using the method illustrated in this chapter. The emissions in Table 21.1 for the idle power setting likely fit this condition.

Extending the example of aircraft emissions further, it is clear that emission sources that move are very complex to address. Aircraft emissions are released to the atmosphere at various points during a flight, varying vertically from ground level to about 13,000 m altitude, and horizontally from the departure and landing points. The method described in this chapter for fixed terrestrial sources would need to be extended to handle moving emission sources.

21.4. Effects of Emissions on the Atmosphere

The effects on the atmosphere of exergy changes due to exhaust-gas emissions have been analyzed by Ao et al. (2012), who investigate the exergy change of the surroundings of exhaust-gas emitting ports, its probable effects on the atmosphere, and the stable state changing point of the atmosphere. A nonlinear and dynamic exergy-change function is utilized, which accounts for the flow direction of the exhaust gas in the absence of a local wind. The results suggest that exergy can be used as a state function to describe the change, the stability and the order of the atmosphere as well as other systems.

21.5. Closing Remarks

The exergy distribution characteristics of pollutants emitted from a smokestack provide a means by which exergy can potentially provide a pollution assessment standard that captures in one or several measures many of the characteristics of pollutants emitted from combustion smokestacks, making it easier to identify the magnitudes and locations of the most significant environment and ecological impacts and hazards. Also, the exergy-based environmental impact measure based on tolerance limits is a useful extension that may provide the basis for an exergy-based standard for environmental acceptability. Possible extensions of the methods to other pollution sources, such as those associated with aircraft, are also possible.

Chapter 22

COGENERATION

OVERVIEW

Several case studies are presented that apply exergy-based methods to cogeneration, including an EXCEM analysis of a cogeneration plant and the application of an exergy-based method for allocating emissions for cogeneration systems. The EXCEM case study demonstrates the intricacies and applicability of the method and the enhanced understanding it provides into environmental, ecological, technical and economic performance. The exergy-based emissions allocation case study demonstrates that the methodology is rational and useful for appropriately allocating emissions among the different commodities in cogeneration, and provides a sensible basis for a meaningful overall approach for emissions trading.

Case studies are presented for the cogeneration of electricity and heat, or combined heat and power (CHP), which illustrate exergy-based methods relating to the environment and ecology. First, an EXCEM analysis is illustrated for a cogeneration plant, illustrating the EXCEM methodology described in Section 10.8. Then, the allocation of carbon dioxide emissions for cogeneration plants using exergy, as described in Chapter 17, is illustrated, demonstrating the benefits of the approach.

22.1. EXCEM ANALYSIS OF A COGENERATION PLANT

22.1.1. Plant Description

The cogeneration plant considered in this EXCEM analysis cogenerates two products (electricity and heat) and consists of two devices:

- A boiler, which produces 17.9 kg/s of steam at a pressure of 44.2 atm and a temperature of 399°C.
- A turbine generator through which the steam expands until it is exhausted at 0.065 atm and 37.8°C.

Steady-state operation is considered, and data are based on a previous investigation of a steady-state cogeneration plant (Reistad and Gaggioli, 1980).

The reference environment used in the energy and exergy evaluations has a temperature of 10°C, a pressure of 1 atm and a composition as for the reference-environment model described in Table 6.1.

22.1.2. EXCEM Flows

Exergy flow and consumption rates are illustrated in Figures 22.1a, energy flow rates in Figure 22.1b, and cost flow and creation rates in Figures 22.1c. Inputs to the boiler of feedwater, for which the associated flow rates of energy, exergy and cost are approximately zero, are omitted from the diagram. Costs have been adjusted from those originally reported to 2007 US dollars using the US Consumer Price Index. Values of cost generation rate are evaluated using an amortization factor of 0.08 and a load factor of 0.7 as follows:

$$\text{Cost generation rate} = (\text{Capital cost} \times \text{Amortization factor}) / (\text{Load factor}) \tag{22.1}$$

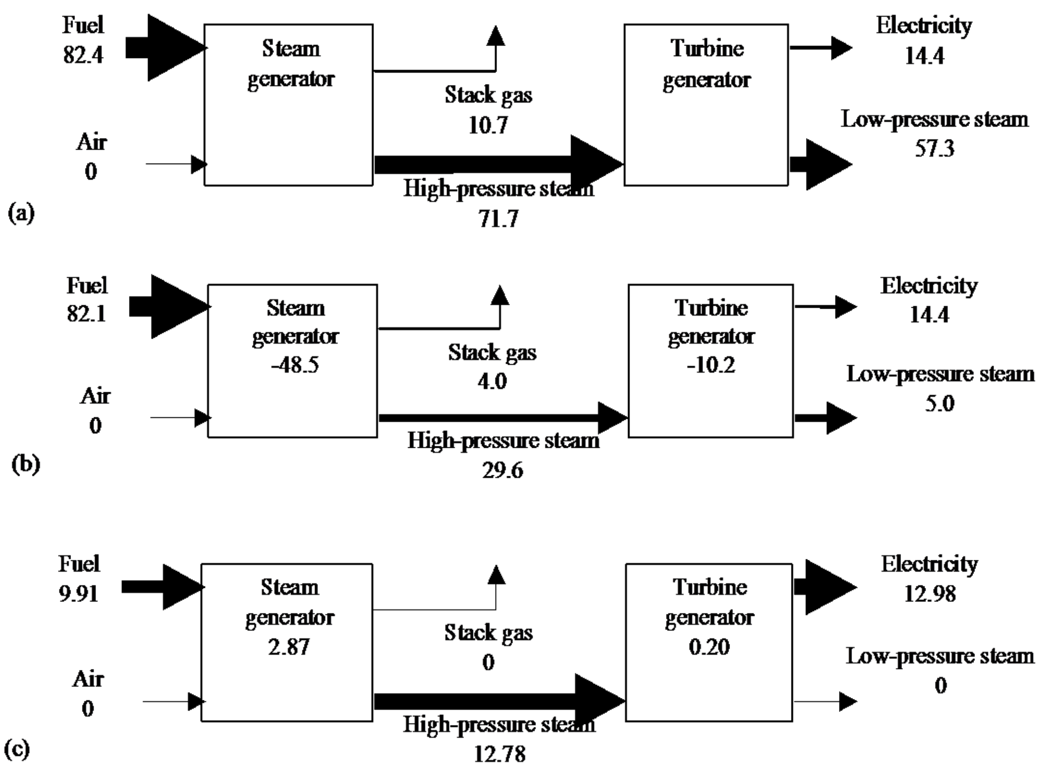

Figure 22.1. Flow rates of commodities through a cogeneration plant for the production of electricity and low-pressure steam: (a) energy (in MW), (b) exergy (in MW) and (c) cost (in 2007 US M$/yr). Rates of exergy consumption and cost creation are given within the devices in (b) and (c), respectively. Thicknesses of flow lines are proportional to the magnitude of the flow rate of the relevant commodity.

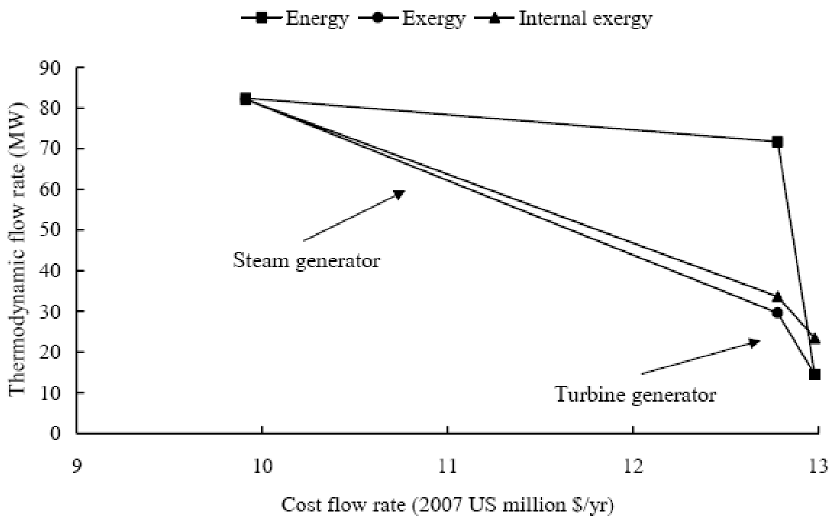

Figure 22.2. Variation with cost flow rate of energy, exergy and exergy consumption rates for devices in a cogeneration plant.

The flow rates of exergy and cost at different points in the cogeneration process are shown in Figure 22.2. A monotonically decreasing composite line is traced in all cases. The slopes and magnitudes of the individual lines indicate characteristics of the corresponding devices. Figure 22.2 illustrates the general trade-off that is typically made between cost and efficiency (or inefficiency) in real systems. Energy flow rates are also shown in Figure 22.2 but, although somewhat similar to the exergy curves, they are misleading because they treat all energy losses equally.

22.2. EXERGY-BASED ALLOCATION OF COGENERATION EMISSIONS

The different methods for allocating carbon dioxide emissions for cogeneration plants that are described in Chapter 17 are illustrated for three case studies in this section. In the first two, the different methods of allocating carbon dioxide emissions are illustrated for actual cogeneration plants. In the third case, a hypothetical cogeneration scenario is compared to equivalent separate processes for producing thermal and electrical energy, and the implications of the different allocation methods are discussed. In addition, the third case is used to illustrate how the results could be used to determine carbon dioxide emission credits that might be used in emissions trading. The case studies are intended to demonstrate the types of values that can be obtained using the different methods, and to illustrate the attributes of the different methods.

The case studies are intended to address the question of how to allocate emissions for an energy system that has multiple products and multiple inputs, and include the following:

- Applications to several example cogeneration systems of the emissions-allocation methods based on exergy and other approaches, and a comparison of the results.
- Explanations of how the results can be used in future emissions-trading concepts.

22.2.1. Illustrations of CO_2 Emissions Allocations for Two Actual Cogeneration Plants

The two example cases considered are

- the University of Toronto Cogeneration System, and
- the Cornwall Cogeneration and District Energy System.

Descriptions of the Case Studies

Data for these systems have been drawn mainly from information from Wiggin (1997) and Consumers Gas (1995) that have been compiled by Klein (1999c).

The basic technical parameters for the two cogeneration systems considered, including data on the cogeneration engine and the cogenerated heat, are summarized in Table 22.1. Some general thermodynamic parameters for the cogeneration systems considered that are specified in the literature (Wiggin, 1997; Consumers Gas, 1995) are presented in the top part of Table 22.2.

Energy and Exergy Values

Energy and exergy data for the cogeneration systems considered are presented in the bottom two parts of Table 22.2. These data include efficiencies and flow rates for products and inputs, and are based on data in the literature (Wiggin, 1997; Consumers Gas, 1995) and evaluations by the present author.

The energy and exergy flow rates for the fuel are similar, as are the energy and exergy flow rates for the electrical products. However, the product thermal energy and thermal exergy rates differ markedly for both processes, as do the energy and exergy efficiencies.

Table 22.1. Technical parameters for the cogeneration systems considered

Parameter	University of Toronto Cogeneration System*	Cornwall Cogeneration and District Energy System**
Engine type	Gas turbine	Two reciprocating engines
Heat use	Heating of campus using 6 km steam tunnel system	Municipal district heating using 4.5 km hot-water distribution network
Heat quantity and type (base load)	30,000 lb/hr of 200 psi steam	7 MW via 120°C and 1585 kPa steam
Supplemental firing	Heat recovery steam generator can be supplementary-fired to 90,000 lb/hr steam at 200 psi	None
Environmental controls	Water injection to control nitrogen oxide emissions (to 42 ppm)	Engines use lean-burn technology
Installation date	1993	1995

* Source: Consumers Gas (1995).

** Source: Wiggin (1997).

Table 22.2. Specified and evaluated thermodynamic parameters for the cogeneration systems considered*

Parameter	University of Toronto Cogeneration Plant	Cornwall Cogeneration and District Energy System
General thermodynamic parameters		
Fuel type**	Natural gas	Natural gas
Fuel input rate (kg/s)	0.3949	0.2660
Thermal-product type	Steam (dry saturated)	Hot water
Thermal-product temperature (°C)	197.6	120
Thermal-product absolute pressure (bar)	14.8	16.85
Thermal-product flow rate (kg/s)	3.78	15.12
Energy parameters		
Fuel energy input rate (MW)	19.75	13.3
Electrical energy generation rate (MW)	6	5
Product thermal energy rate (MW)	10.393	7
Energy efficiency (%)***	83	90
Exergy parameters		
Fuel exergy input rate (MW)****	20.35	13.70
Electrical exergy generation rate (MW)	6	5
Product thermal exergy rate (MW)	3.654	1.134
Exergy efficiency (%)	46.0	44.8

* Reference-environment temperature and pressure are 10°C and 1 bar, respectively.
** Natural gas is modeled as methane in calculations.
*** Energy efficiencies provided in sources are assumed to be based on lower heating value.
**** Ratio of chemical exergy to lower heating value for methane is evaluated as 1.03 based on data in Moran et al. (2011).

Emissions Allocations

The results of applying the methods for allocating CO_2 of emissions are presented for the University of Toronto cogeneration plant in Table 22.3 and Figure 22.3, and for the Cornwall Cogeneration and District Energy System in Table 22.4 and Figure 22.4.

For both example cases, it is clear that the allocations of CO_2 emissions vary markedly, depending on the allocation method used. This author contends, as discussed throughout this chapter, that the exergy-based allocations are the most appropriate. Thus, using the other emissions allocation methods can be misleading, since the resulting emissions may deviate widely from those obtained using the exergy-based method.

Several problems with the other allocation methods are illustrated in Tables 22.3 and 22.4 and Figures 22.3 and 22.4. Some examples follow:

- In one case (where the allocation is based on incremental fuel consumption to heat production, for the Cornwall system), the absurd situation exists in which the allocations of emissions to the thermal product are evaluated to be negative and the allocations to the electrical product to exceed 100%. This result is simply a consequence of the flaws in that allocation method and its use of an energy efficiency η_{pp} for an independent device for providing the same electrical energy as the cogeneration system (e.g., a reference power plant). Here, a value of η_{pp} = 35% is used. If, instead, the value of η_{pp} is selected such that η_{pp} = 38%, then the allocations of carbon dioxide emissions to both products would be positive and less than 100%.

- For the allocation method based on economic value of products, the results depend on the value of the ratio of the economic value of the electricity produced c_E to the economic value of the thermal energy produced c_Q. The value of this ratio, even considering only the present time, varies with location. In Tables 22.3 and 22.4, therefore, the values of the emission allocations for this method are left variable. In Figures 22.3 and 22.4, a range of c_E/c_Q values are considered.

To appreciate the wide range of possible emissions allocations possible when using the method based on economic value of products, the emissions allocations are plotted in Figure 22.5 for a wide range of c_E/c_Q values, for both the University of Toronto cogeneration plant and the Cornwall Cogeneration and District Energy System. At a cost ratio of 1 (i.e., $c_E = c_Q$), electrical and thermal energy have the same economic value, while electricity is the more valuable commodity when $c_E/c_Q > 1$ and heat is more valuable when $c_E/c_Q < 1$. It is observed in Figure 22.5 that all emissions are attributable to heat for a value ratio $c_E/c_Q = 0$. As the value of the ratio increases, more emissions are shifted from heat to electricity. As the ratio approaches infinity, the emissions approach being entirely attributable to electricity.

Table 22.3. Allocation of emissions for University of Toronto Cogeneration Plant*

Emission-allocation method	Emission allocation (%)	
	To electrical product	To thermal product
Based on exergy content of products	62.1	37.9
Based on energy content of products	36.6	63.4
Allocation of incremental fuel use to electrical production**	41.5	58.5
Allocation of incremental fuel use to heat production***	86.8	13.2
Based on a shared emission savings between electricity and heat	59.8	40.2
Based on economic value of products****	$5/[5 + 7(c_E/c_Q)^{-1}]$ 100%	$7/(5c_E/c_Q + 7)$ 100%

* Reference-environment temperature and pressure are T_o = 10°C and P_o = 1 bar, respectively.

** An efficiency of 90% is assumed for the boiler that would have been used in the production of the same amount of heat as produced by the cogeneration system.

*** An efficiency of 35% is assumed for the power plant that would have been used in the production of the same amount of electricity as produced by the cogeneration system.

**** The parameter c_E/c_Q denotes the ratio of the economic value of the electricity produced to the economic value of the thermal energy produced.

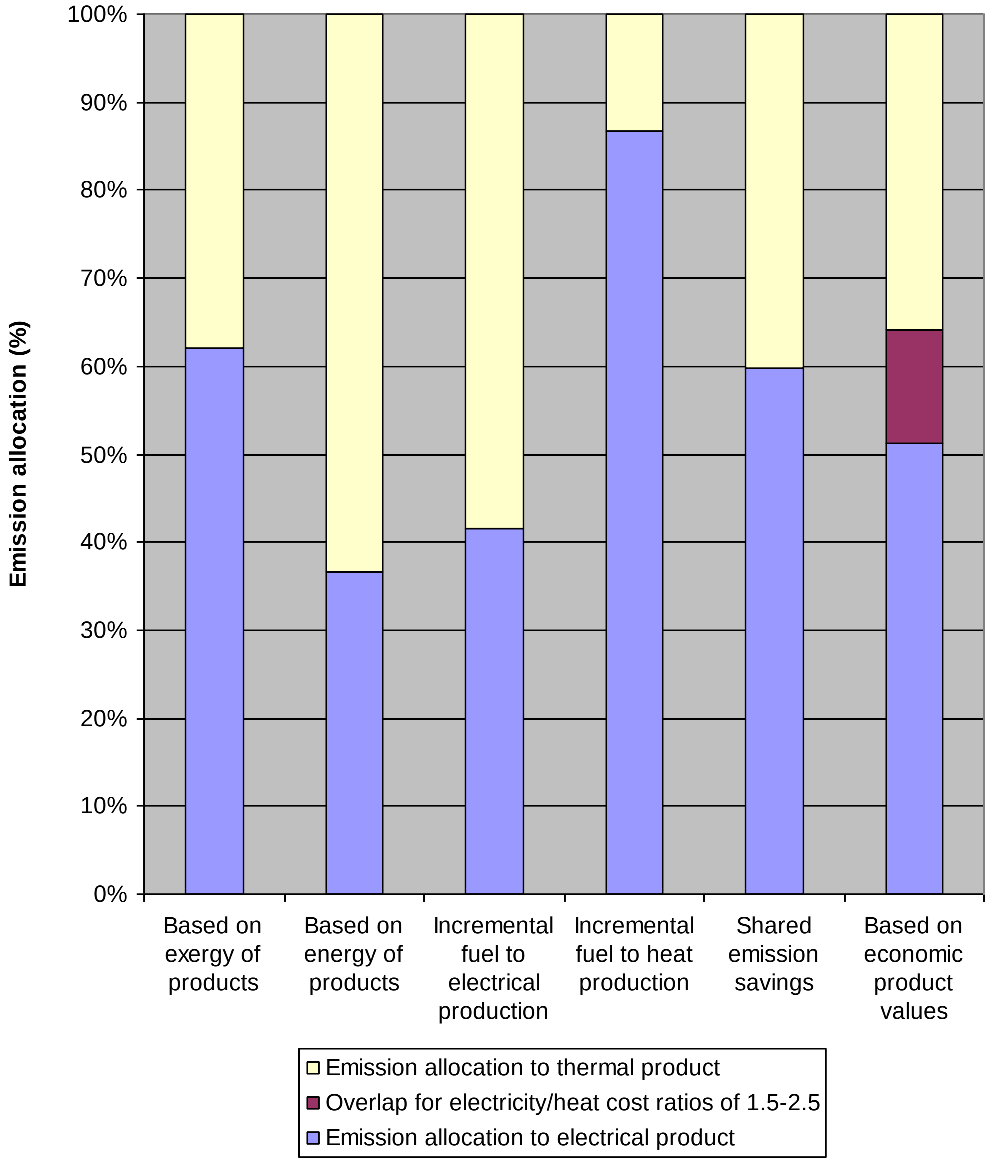

Figure 22.3. Allocation of emissions for University of Toronto cogeneration plant (based on data in Table 22.3).

22.2.2. Illustrative Comparison of CO_2 Emissions Allocations for a Cogeneration Plant and Equivalent Independent Plants

Description of Scenario

In this section, a hypothetical cogeneration scenario is compared to equivalent separate processes for producing the same thermal and electrical energy, and the implications of the different allocation methods are discussed. The main characteristics of the processes being compared are as follows:

- The hypothetical cogeneration system produces 4 MW of electrical power and 4 MW of thermal power from a fuel energy rate of 10 MW. The energy efficiency is 80%.
- The separate processes consist of (i) an electricity generation system that produces 4 MW of electrical power from a fuel energy input rate of 10 MW, and (ii) a heating system that produces 4 MW of thermal power from a fuel energy input rate of 5 MW. The energy efficiency of the overall (combined) process is 53% (i.e., 8/15 × 100%).

In both cases, the input fuel is natural gas. The carbon dioxide emissions for natural gas are taken to be 50 kg CO_2/GJ natural gas.

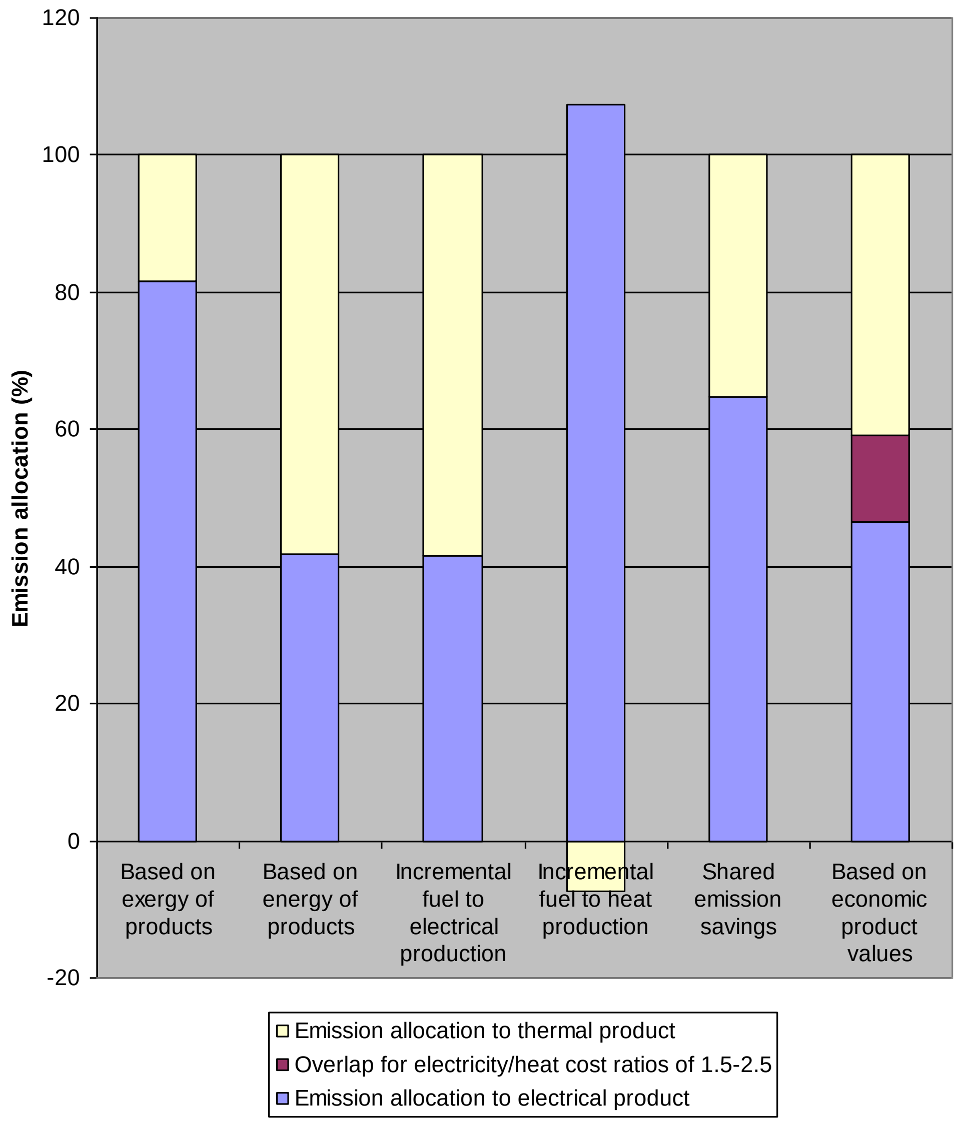

Figure 22.4. Allocation of emissions for Cornwall cogeneration and district heating system (based on data in Table 22.4).

Table 22.4. Allocation of emissions for the Cornwall Cogeneration and District Heating System*

Emission-allocation method	Emission allocation (%)	
	To electrical product	To thermal product
Based on exergy content of products	81.5	18.5
Based on energy content of products	41.7	58.3
Allocation of incremental fuel use to electrical production**	41.5	58.5
Allocation of incremental fuel use to heat production***	107.4	–7.4
Based on a shared emission savings between electricity and heat	64.7	35.3
Based on economic value of products****	$6/[6+10.4\ (c_E/c_Q)^{-1}]$ 100%	$10.4/(6c_E/c_Q+10.4)$ 100%

* Reference-environment temperature and pressure are T_o = 10°C and P_o = 1 bar, respectively.
** An efficiency of 90% is assumed for the boiler that would have been used in the production of the same amount of heat as produced by the cogeneration system.
*** An efficiency of 35% is assumed for the power plant that would have been used in the production of the same amount of electricity as produced by the cogeneration system.
**** The parameter c_E/c_Q denotes the ratio of the economic value of the electricity produced to the economic value of the thermal energy produced.

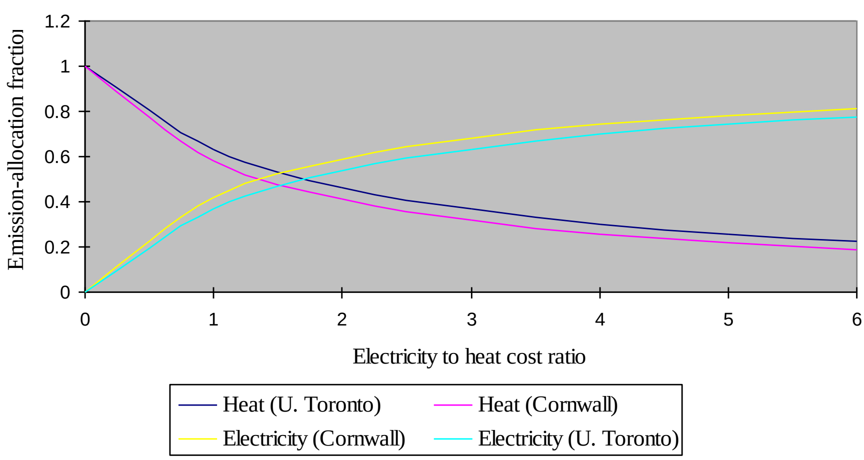

Figure 22.5. CO_2 emissions allocations based on economic values of products for two cases.

The 4 MW of thermal energy produced in each case is taken to be made up of 2 MW of steam and 2 MW of hot water. For simplicity, the state of the steam is taken to be the same as for the steam produced in the University of Toronto Cogeneration Plant described in the previous section (dry saturated steam at a pressure of 200 psi gauge), while the state of the hot water is taken to be the same as for the hot water produced in the Cornwall Cogeneration and District Energy System described in the previous section (hot water at a temperature of 120°C and a pressure of 1585 kPa gauge).

Table 22.5. Specified and evaluated thermodynamic parameters for the cogeneration and independent processes considered*

Parameter	Independent processes			Cogeneration
	Heating	Electricity generation	Overall (combined)	
General thermodynamic parameters				
Fuel type	Natural gas	Natural gas	Natural gas	Natural gas
Fuel energy input rate (MW)	5	10	15	10
Thermal-product type(s)	Steam (dry sat.) Hot water	–	Steam (dry sat.) Hot water	Steam (dry sat.) Hot water
Thermal-product temperature (°C)	197.6 (steam) 120 (hot water)	–	197.6 (steam) 120 (hot water)	197.6 (steam) 120 (hot water)
Thermal-product absolute pressure (bar)	14.8 (steam) 16.85 (hot water)	–	14.8 (steam) 16.85 (hot water)	14.8 (steam) 16.85 (hot water)
Thermal-product flow rate (kg/s)	0.727 (steam) 4.32 (hot water)	–	0.727 (steam) 4.32 (hot water)	0.727 (steam) 4.32 (hot water)
Energy parameters				
Fuel energy input rate (MW)	5	10	15	10
Electrical energy generation rate (MW)	–	4	4	4
Product thermal energy rate (MW)				
Steam	2	–	2	2
Hot water	2	–	2	2
Total	4	–	4	4
Energy efficiency (%)**	80	40	53.3	80
Exergy parameters				
Fuel exergy input rate (MW)***	5.15	10.3	15.45	10.3
Electrical exergy generation rate (MW)	–	4	4	4
Product thermal exergy rate (MW)				
Steam	0.777	–	0.777	0.777
Hot water	0.323	–	0.323	0.323
Total	1.100	–	1.100	1.100
Exergy efficiency (%)	21.4	38.8	33.0	49.5

* Reference-environment temperature and pressure are 10°C and 1 bar, respectively.
** Energy efficiencies provided in sources are assumed to be based on lower heating value.
*** Ratio of chemical exergy to lower heating for methane is 1.03 based on data in Moran et al. (2011).

Energy and Exergy Values

Energy and exergy data evaluated by the present author for the cogeneration and independent processes for heating and electricity generation are presented in Table 22.5, including efficiencies and product and input flow rates. The results in Table 22.5 demonstrate that the energy and exergy flow rates for the fuel are similar, as are the energy and exergy flow rates for the electrical products.

Table 22.6. Allocation (in %) of emissions for the cogeneration and independent processes considered*

Process	Emission-allocation method	Emission allocation (%)	
		To electrical product	To thermal product
Independent			
Heating		0	100
Electricity generation		100	0
Overall (combined)		66.7	33.3
Cogeneration	Based on exergy content of products	78.4	21.6
	Based on energy content of products	50.0	50.0
	Allocation of incremental fuel consumption to electrical production**	55.6	44.4
	Allocation of incremental fuel consumption to heat production***		
	Assuming a reference power plant efficiency of η_{pp} = 35%	114.3	–14.3
	Assuming a reference power plant efficiency of η_{pp} = 40%	100	0
	Based on a shared emission savings between electricity and heat		
	Assuming a reference power plant efficiency of η_{pp} = 35%	72.0	28.0
	Assuming a reference power plant efficiency of η_{pp} = 40%	69.2	30.8
	Based on economic value of products****		
	Assuming an electrical-to-thermal cost ratio of c_E/c_Q = 1.5	60.0	40.0
	Assuming an electrical-to-thermal cost ratio of c_E/c_Q = 1.8	64.3	35.7
	Assuming an electrical-to-thermal cost ratio of c_E/c_Q = 2.1	67.7	32.3

* Reference-environment temperature and pressure are T_o = 10°C and P_o = 1 bar, respectively.

** An efficiency of 90% is assumed for the boiler that would have been used in the production of the same amount of heat as produced by the cogeneration system.

*** Efficiencies of 35% and 40% are considered for the power plant that would have been used in the production of the same amount of electricity as produced by the cogeneration system.

**** The parameter c_E/c_Q denotes the ratio of the economic value of the electricity produced to the economic value of the thermal energy produced.

Table 22.7. Allocation (in g CO_2/s) of emissions for the cogeneration and independent processes considered*

Process	Emission-allocation method	Emission allocation (g CO_2/s)		
		To electrical product	To thermal product	Total
Independent				
Heating		0	250	250
Electricity generation		500	0	500
Overall (combined)		500	250	750
Cogeneration	Based on exergy content of products	392	108	500
	Based on energy content of products	250	250	500
	Allocation of incremental fuel consumption to electrical production**	278	222	500
	Allocation of incremental fuel consumption to heat production***			
	Assuming a reference power plant efficiency of η_{pp} = 35%	572	–72	500
	Assuming a reference power plant efficiency of η_{pp} = 40%	500	0	500
	Based on a shared emission savings between electricity and heat			
	Assuming a reference power plant efficiency of η_{pp} = 35%	360	140	500
	Assuming a reference power plant efficiency of η_{pp} = 40%	346	154	500
	Based on economic value of products****			
	Assuming an electrical-to-thermal cost ratio of c_E/c_Q = 1.5	300	200	500
	Assuming an electrical-to-thermal cost ratio of c_E/c_Q = 1.8	322	178	500
	Assuming an electrical-to-thermal cost ratio of c_E/c_Q = 2.1	339	161	500

* Reference-environment temperature and pressure are T_o = 10°C and P_o = 1 bar, respectively.

** An efficiency of 90% is assumed for the boiler that would have been used in the production of the same amount of heat as produced by the cogeneration system.

*** Efficiencies of 35% and 40% are considered for the power plant that would have been used in the production of the same amount of electricity as produced by the cogeneration system.

**** The parameter c_E/c_Q denotes the ratio of the economic value of the electricity produced to the economic value of the thermal energy produced.

However, the product thermal energy and thermal exergy rates differ markedly for both processes, as do the energy and exergy efficiencies. Two particular results are observed in Table 22.5 regarding efficiency:

- Cogeneration is much more efficient (on energy or exergy bases) than the independent processes for producing the same thermal and electrical products.
- The exergy efficiencies are lower than the energy efficiencies, reflecting the fact that the thermal energy products are both of lower usefulness (or quality) than electricity. Of the two thermal products, the exergy values indicate that the usefulness of the steam is greater than that for the hot water.

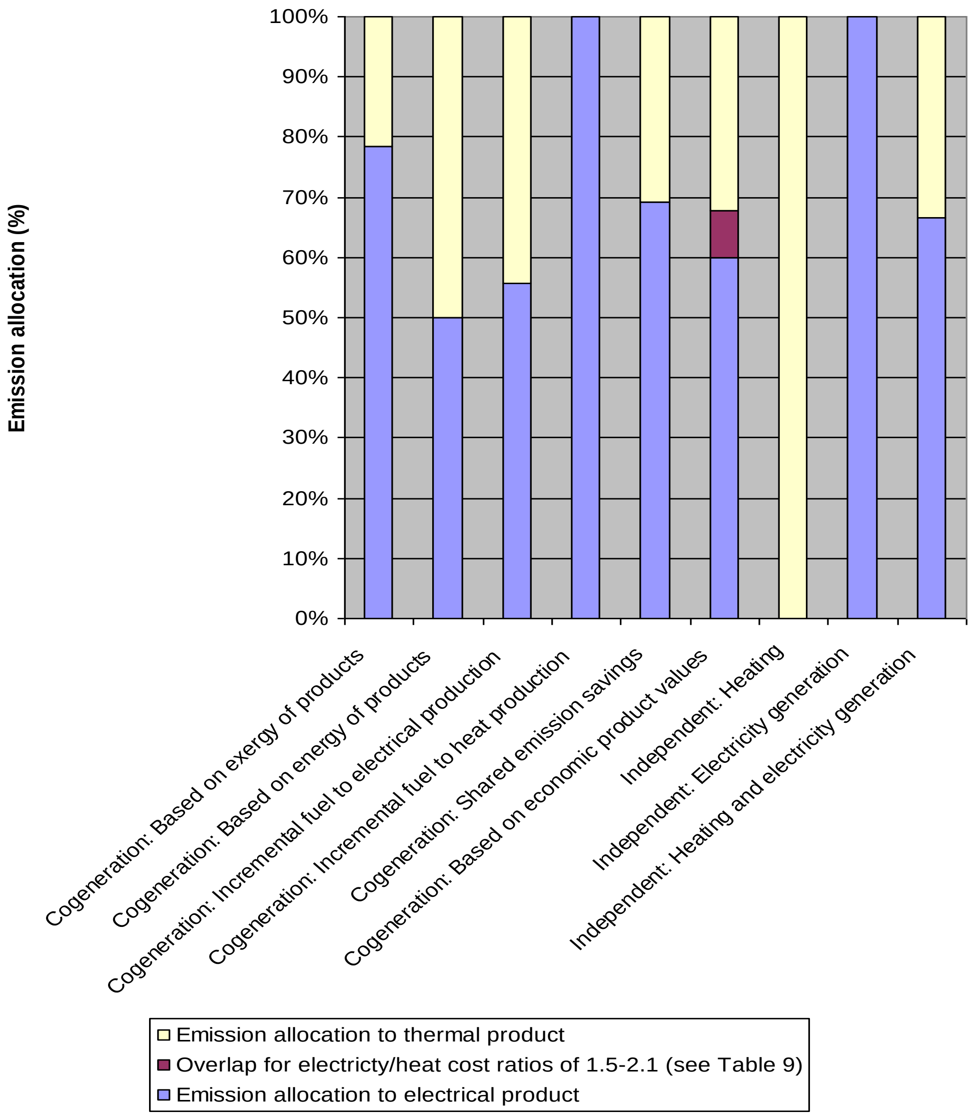

Figure 22.6. Allocation of emissions (in %) for independent and cogeneration processes considered (based on data in Table 22.6 and a reference power plant efficiency of 40%).

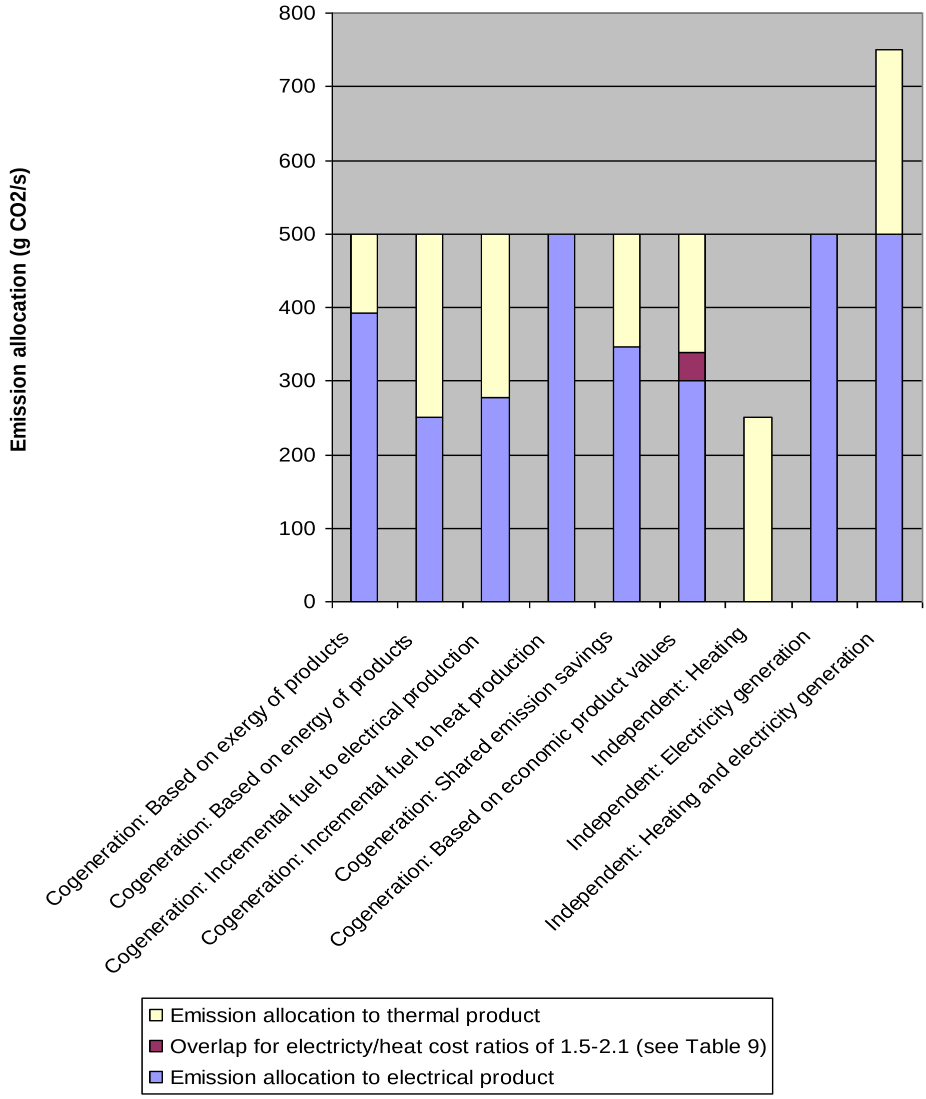

Figure 22.7. Allocation of emissions (in g CO_2/s) for independent and cogeneration processes considered (based on data in Table 22.7 and a reference power plant efficiency of 40%).

Emissions Allocations

The results of applying the methods for allocating CO_2 of emissions for the cogeneration and independent processes are presented in Tables 22.6 and 22.7 and Figures 22.6 and 22.7. Percentage breakdowns are shown in Table 22.6 and Figure 22.6, while absolute emissions rates are shown in Table 22.7 and Figure 22.7.

For the independent processes, there exists no ambiguity regarding the allocations of emissions to the thermal and electrical products. For the cogeneration process, the appropriate method to allocate emissions is not clear, so the allocations methods discussed earlier are applied. The allocations of CO_2 emissions are seen to vary markedly, depending on the allocation method used.

This author contends, as discussed throughout this chapter, that the exergy-based allocations are the most appropriate. Thus, using the other emissions allocation methods can be very misleading, since the resulting emissions may deviate widely from those obtained using the exergy-based method.

Again, some of the problems with the other allocation methods are illustrated in Tables 22.6 and 22.7 and Figures 22.6 and 22.7:

- Where the allocation is based on incremental fuel consumption to heat production, the allocations of emissions to the thermal product are evaluated to be negative and the allocations to the electrical product to exceed 100%. This impractical result stems from flaws in that allocation method and its use of an energy efficiency a reference power plant η_{pp}, set to 35%. If, alternatively, η_{pp} is fixed at 40%, the allocations of carbon dioxide emissions to both products do not exceed 100%.
- The results depend on the ratio of the economic values of the produced electricity c_E and thermal energy c_Q, for the allocation method based on economic value of products. The value of this ratio varies with time and location. For illustration, we consider here economic parameter values from a U.S. report (Harrell, 2002), which allow the cost of electricity to be approximated as US$0.060/kWh and the cost of steam as US$0.0334. The electrical-to-thermal cost ratio is then c_E/c_Q = 1.8. In Tables 22.6 and 22.7, therefore, this value is used. Also, values of c_E/c_Q of 1.5 and 2.1 are used to indicate the sensitivity of the allocations to the cost ratio.

22.2.3. Determining CO_2 Emissions Credits for Trading Purposes from Switching to Cogeneration from Equivalent Independent Plants

In this section, the case illustrated in Section 22.2.2 is used to illustrate how the results could be used to determine carbon dioxide emission credits that might be used in emissions trading. Here, we consider two energy users, one of electricity and one of thermal energy. The types of thermal energy used are the same as those described in Section 22.2.2. The decrease in CO_2 emissions attributable to the energy users are evaluated, when each switches from obtaining the energy required (electricity or thermal energy) from a producer of only the required energy to a supplier using cogeneration. The decrease in CO_2 emissions for each energy user is its CO_2 emissions credits. The characteristics of the cogeneration plant and the independent electrical power and heating plants are as in Section 22.2.2.

CO_2 Emissions Credits when an Electricity User Switches to Cogeneration

In this situation, we consider an electrical consumer who normally obtains electricity from a power plant. We wish to determine the decrease in CO_2 emissions attributable to that consumer (i.e., the CO_2 emissions credit for the consumer) if the consumer switches to obtaining electricity from a supplier that uses cogeneration.

We follow a multi-step calculation procedure. For simplicity, we consider a unit energy use by the consumer of 1 GJ of electricity. Parameter values that characterize the technologies considered are drawn from Section 22.2.2.

The CO_2 emissions attributable to the consumer when obtaining electricity from a power plant can be evaluated as the product of the fuel use in the power plant and the carbon dioxide emissions factor for the fuel. That is,

CO_2 emissions = (Fuel use in power plant)(Fuel CO_2 emissions factor)
= (Electricity use/Power plant efficiency)(Fuel CO_2 emissions factor)
= (1 GJ electricity/0.40 GJ electricity/GJ fuel)(50 kg CO_2/GJ fuel)
= 125.0 kg CO_2/GJ electricity

The total CO_2 emissions of the cogeneration plant (to produce 1 GJ of electricity as well as thermal energy) can be evaluated as the product of the total fuel use in the cogeneration plant and the carbon dioxide emissions factor for the fuel. That is,

CO_2 emissions = (Fuel use in cogeneration plant)(Fuel CO_2 emissions factor)
= (Elec. use/Cogen. efficiency for elec.)(Fuel CO_2 emissions factor)
= (1 GJ electricity/0.40 GJ electricity/GJ fuel)(50 kg CO_2/GJ fuel)
= 125.0 kg CO_2/GJ electricity

Of the total CO_2 emissions of the cogeneration plant (to produce 1 GJ of electricity as well as thermal energy), the CO_2 emissions attributable to the consumer when obtaining electricity from cogeneration can be evaluated as the fraction of the total CO_2 emissions of the cogeneration plant attributed to electricity production. In this chapter, it is argued that the division of CO_2 emissions for cogeneration among electrical and thermal products should be based on the exergy contents of the products. For the present case, it is shown in Section 22.2.2 that 78.4% of the total CO_2 emissions for the cogeneration plant should be attributed to the electrical product based on exergy (see Table 22.6). Thus, the CO_2 emissions attributable to the consumer when obtaining electricity via cogeneration can be evaluated as follows:

CO_2 emissions for user = (Total CO_2 emissions of cogen. plant)(Fraction for electricity)
= (125.0 kg CO_2/GJ electricity)(0.784)
= 98.0 kg CO_2/GJ electricity

Finally, the CO_2 emissions credit for switching to cogeneration, evaluated as the decrease in CO_2 emissions attributable to the electricity user, can be evaluated as the difference between the CO_2 emissions attributable to the consumer when obtaining electricity from a power plant and from a cogeneration plant. That is,

CO_2 emissions credit = (CO_2 emissions for elec. from power plant attrib. to consumer)
– (CO_2 emissions for elec. from cogen. attributed to consumer)
= (125 kg CO_2/GJ electricity) – (98.0 kg CO_2/GJ electricity)
= 27.0 kg CO_2/GJ electricity

The results (see Table 22.8 and Figure 22.8) can assist in evaluating CO_2 emissions credits for electricity users, for trading and other purposes.

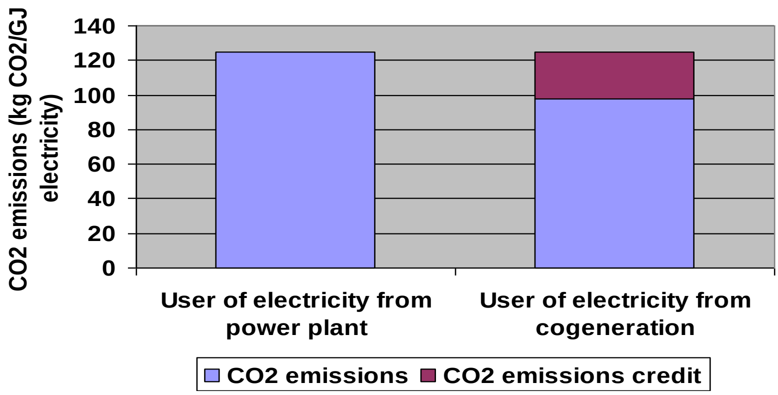

Figure 22.8. Carbon dioxide emissions for electricity generation via power plant and cogeneration, and carbon dioxide emissions credit.

Table 22.8. Carbon dioxide emissions and emissions credit for switching to cogeneration for electricity and heat users*

	CO_2 emissions (kg)
For user of electricity (1 GJ)	
CO_2 emissions for user of electricity from power plant	125.0
CO_2 emissions for user of electricity from cogeneration plant	98.0
CO_2 emissions credit for user of electricity for switching from power plant to cogeneration plant	27.0
For user of heat (1 GJ)	
CO_2 emissions for user of heat from heating plant	62.5
CO_2 emissions for user of heat from cogeneration plant	27.0
CO_2 emissions credit for user of heat for switching from heating plant to cogeneration plant	35.5

* Allocation of emissions from cogeneration to electrical and heat products is determined based on exergy contents of products.

CO_2 Emissions Credits when a Heat User Switches to Cogeneration

We now consider a heat consumer who normally obtains heat from a heating plant, and determine the decrease in CO_2 emissions attributable to that consumer (i.e., the CO_2 emissions credit for the consumer) if the consumer switches to a cogenerating heat supplier.

Again, we use a multi-step calculation procedure, and consider for simplicity a unit energy use by the consumer of 1 GJ of thermal energy. The thermal energy used by the consumer is of the type described in Section 22.2.2, and parameter values that characterize the technologies considered are drawn from that section.

The CO_2 emissions attributable to the consumer when obtaining heat from a heating plant can be evaluated as the product of the fuel use in the heating plant and the carbon dioxide emissions factor for the fuel. That is,

$$\begin{aligned} CO_2 \text{ emissions } &= \text{(Fuel use in heating plant)(Fuel } CO_2 \text{ emissions factor)} \\ &= \text{(Heat use/Heating plant efficiency)(Fuel } CO_2 \text{ emissions factor)} \end{aligned}$$

= (1 GJ heat/0.80 GJ heat/GJ fuel)(50 kg CO_2 /GJ fuel)
= 62.5 kg CO_2 /GJ heat

The total CO_2 emissions of the cogeneration plant (to produce 1 GJ of heat as well as electrical energy) can be evaluated as the product of the total fuel use in the cogeneration plant and the carbon dioxide emissions factor for the fuel. That is,

CO_2 emissions = (Fuel use in cogeneration plant)(Fuel CO_2 emissions factor)
= (Electricity use/Cogen. efficiency for heat)(Fuel CO_2 emissions factor)
= (1 GJ heat/0.40 GJ heat/GJ fuel)(50 kg CO_2 /GJ fuel)
= 125.0 kg CO_2 /GJ heat

Of the total CO_2 emissions of the cogeneration plant (to produce 1 GJ of heat as well as electrical energy), the CO_2 emissions attributable to the consumer when obtaining heat from a cogeneration plant can be evaluated as the fraction of the total CO_2 emissions of the cogeneration plant attributed to heat production. In this chapter, we point out that the division of CO_2 emissions for cogeneration among electrical and thermal products should be based on the exergy contents of the products. For the present case, it was shown in Section 22.2.2 that 21.6% of the total CO_2 emissions for the cogeneration plant should be attributed to the thermal product based on exergy (see Table 22.6). Thus, the CO_2 emissions attributable to the consumer when obtaining heat from a cogeneration plant can be evaluated as follows:

CO_2 emissions for user = (Total CO_2 emissions of cogeneration plant)(Fraction for heat)
= (125.0 kg CO_2 /GJ heat)(0.216)
= 27.0 kg CO_2 /GJ heat

Finally, the CO_2 emissions credit for switching to cogeneration, evaluated as the decrease in CO_2 emissions attributable to the heat user, can be evaluated as the difference between the CO_2 emissions attributable to the consumer when obtaining heat from a power plant and from a cogeneration plant. That is,

CO_2 emissions credit = (CO_2 emissions for heat from heating plant attrib. to consumer)
– (CO_2 emissions for heat from cogen. attributed to consumer)
= (62.5 kg CO_2 /GJ heat) – (27.0 kg CO_2 /GJ heat)
= 35.5 kg CO_2 /GJ heat

The results are presented in Table 22.8 and illustrated in Figure 22.9, and can assist in evaluating CO_2 emissions credits for thermal energy users, for trading and other purposes.

CO_2 Emissions Credits for Other Cases

The procedures illustrated in the previous two subsections can be formalized for variations of the cases considered here, as well as for various other cases. Other situations that could be considered include on- and off-site plants, different fuels, different thermal energy requirements and trigeneration systems.

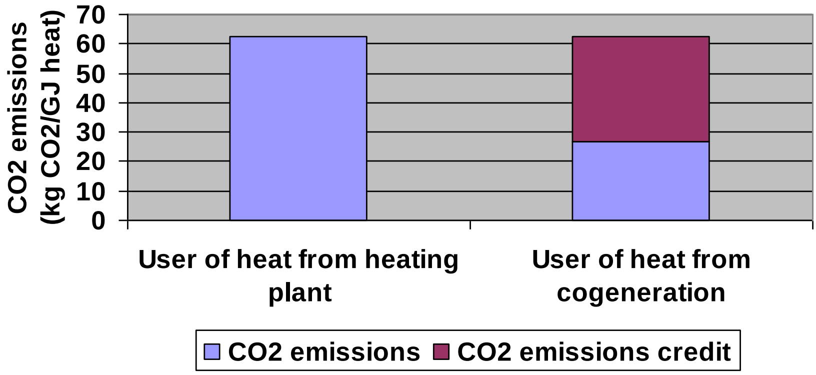

Figure 22.9. Carbon dioxide emissions for heat production via heating plant and cogeneration, and carbon dioxide emissions credit.

22.3. Closing Remarks

The case studies illustrate for cogeneration the benefits of exergy-based methods related to environment and ecology. EXCEM analysis provides enhanced understanding into environmental, ecological, technical and economic performance. The exergy-based emissions allocation methodology has a rational foundation is shown to be useful for appropriately allocating emissions among the different commodities in cogeneration, and to provide a sensible basis for a meaningful overall approach for emissions trading. The case studies can aid designers of energy systems and decision and policy makers in companies and government, through the selection and design of better energy technologies, based on environmental and ecological considerations.

Chapter 23

NUCLEAR ELECTRICITY GENERATION

OVERVIEW

Energy and exergy analyses are described of nuclear power generation, considering technical performance as well as environmental and ecological impacts. The assessments demonstrate the enhanced understanding yielded through exergy analysis into the thermodynamic performance of the process (clearer efficiencies, losses, margins for improvement), as well as resource degradation and the environmental and ecological impacts. It is also explained how the results are skewed by the industry convention of carrying out assessments on the basis of fission heat input.

Energy and exergy analyses are performed of nuclear power generation. Then, the environmental and ecological impacts of the process are assessed using exergy methods. The dependence of the results on the industry convention of carrying out assessments on the basis of fission heat input is explored.

23.1. EXERGY ANALYSIS

An exergy analysis is performed of nuclear power generation to demonstrate how exergy analysis improves understanding of the thermodynamic performance of processes compared to energy analysis, and identifies areas with significant potential for improvement.

The case study considers the Pickering Nuclear Generating Station, a typical nuclear power plant located, which has been operated in Ontario, Canada since 1971 by the provincial utility, Ontario Power Generation (formerly Ontario Hydro) (Ontario Hydro, 1985). Each unit in the nuclear power plant has a net electrical output of approximately 500 MW. A flow diagram for a single unit is shown in Figure 23.1, with symbols identifying the flows described in Table 23.1a for material flows and Table 23.1b for non-material flows (electrical and thermal). The main process data are listed in Table 23.2, and the plant operates as follows (following the four main sections identified in Figure 23.1):

- Preheating. The feedwater temperature is increased in several heaters and the pressure is increased in several pumps, to design levels entering the steam generator.
- Steam generation. Water is converted to steam and steam is reheated using fission heat. Natural uranium is fissioned in the presence of a moderator to produce heat, which is transferred from the reactor to the boiler in the Primary Heat Transport Loop. The flow rate of pressurized heavy water (D_2O) in that loop is 7724 kg/s. The D_2O is heated from 249°C and 9.54 MPa to 293°C and 8.82 MPa in the nuclear reactor. Light-water steam (815 kg/s at 4.2 MPa and 251°C) is produced in the boiler and transported through the secondary heat transport loop. Spent fuel is removed from the reactor, and heat generated in the moderator rejected.
- Power production. The steam from the steam generation section passes through a series of turbine generators attached to a transformer. Each station unit has an 1800-rpm, tandem-compound, impulse-reaction turbine generator containing one double-flow high-pressure cylinder, and three double-flow low-pressure cylinders. Extraction steam from several points on the turbines preheats feedwater in several low- and high-pressure heat exchangers and one spray-type open deaerating heat exchanger. The low-pressure turbines exhaust to the condenser at 5 kPa. Steam exhausted from the high-pressure cylinder passes through a moisture separator and a closed reheater, which uses steam from the boiler as the heat source.
- Condensation. The low-pressure turbines exhaust at 5 kPa to the condenser, where the steam is condensed with cooling water from Lake Ontario, which is restricted to a specified temperature rise.

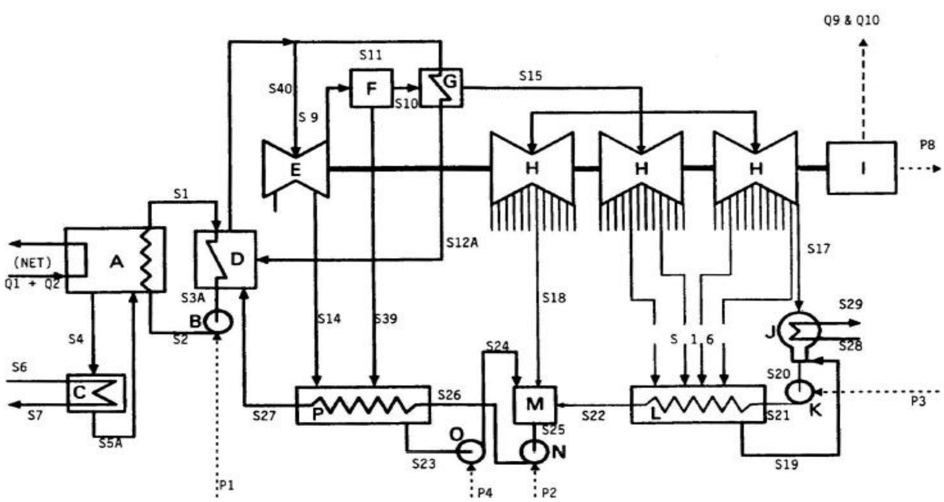

Figure 23.1. Single unit of nuclear power plant. Symbols identifying flows are explained in Table 23.1, and the devices are identified as follows: A: nuclear reactor, B: heavy water pump, C: moderator cooler, D: steam generator, E: high-pressure turbine, F: moisture separator, G: closed reheater, H: low-pressure turbines, I: generator and transformer, J: condenser, K: hot well pump, L: low-pressure heat exchangers, M: open deaerating heat exchanger, N: boiler feed pump, O: pump, P: high-pressure heat exchangers. The plant's four main sections are steam generation (devices A-D), power production (devices E-I), condensation (device J), and preheating (devices K-P). Lines exiting turbines represent flows of extraction steam and flow S16 represents the mixed contents of the four indicated extraction steam flows. The flow of uranium into and out of the nuclear reactor, and the net heat delivered, are indicated.

Table 23.1a. Data for material flows in the nuclear power plant in Figure 23.1

Flow	Intensive flow properties			Flow rates		
	Temperature (°C)	Pressure (MPa)	Vapor fraction*	Mass (kg/s)	Energy (MW)	Exergy (MW)
Light water (H_2O) flows						
S6	15.0	0.101	0.0	1957	0.0	0.0
S7	26.0	0.101	0.0	1957	90.0	1.7
S9	151.8	0.50	0.88	698	1705.5	500.4
S10	160.0	0.50	1.0	603	1629.8	476.5
S11	254.0	4.25	1.0	61	166.9	64.6
S12A	254.0	4.25	0.0	61	63.6	17.8
S14	176.7	9.28	0.90	55	138.7	44.6
S15	238.0	0.450	1.0	603	1733.2	508.4
S16	60.8	0.0207	0.95	83	204.0	28.1
S17	23.3	0.00286	0.90	498	1125.1	44.4
S18	186.1	0.255	1.0	22	61.1	16.0
S19	60.8	0.0207	0.0	83	15.9	1.1
S20	23.3	0.00286	0.0	581	20.2	0.8
S21	23.4	1.48	0.0	581	211.6	1.1
S22	100.2	1.40	0.0	581	207.9	26.5
S23	134.0	0.304	0.0	150	75.0	12.3
S24	134.2	1.48	0.0	150	75.3	12.5
S25	123.7	1.40	0.0	753	344.2	53.2
S26	124.2	5.40	0.0	753	347.9	56.5
S27	163.9	5.35	0.0	753	476.0	96.1
S28	15.0	0.101	0.0	24073	0.0	0.0
S29	26.0	0.101	0.0	24073	1107.2	20.6
S39	160.0	0.618	0.03	95	75.7	23.7
S40	254.0	4.25	1.0	753	2060.0	797.7
Heavy water (D_2O) flows (reactor grade)						
S1	291.9	8.82	0.0	7724	9548.2	2984.2
S2	249.4	9.60	0.0	7724	7875.4	2201.6
S3A	249.0	8.32	0.0	7724	7861.7	2188.6
S4	64.5	0.101	0.0	1000	207.0	16.0
S5A	43.0	0.101	0.0	1000	117.0	5.3

* Vapor fraction is listed as 0 for liquids and 1 for saturated or superheated vapors.

Table 23.1b. Data for electrical and thermal flows in the nuclear power plant in Figure 23.1

Flow	Flow rate (MW)	
	Energy	Exergy
Thermal flows		
Q1	1673.0	1673.0
Q2	90.0	90.0
Q9	5.6	0.0
Q10	5.5	0.0
Electrical flows		
P1	14.3	14.3
P2	3.7	3.7
P3	1.0	1.0
P4	0.2	0.2
P8	544.8	544.8

Table 23.2. Principal process data for full-load operation of the nuclear power plant

Quantity	Value
Flow rates	
Mass (kg/s)	
Primary steam (H_2O)	815
Heavy water loop	724
Cooling water	23,369
Electricity (MW)	
Gross output	542
Internal use	27
Net output	515
Intensive properties	
Temperature (°C)	
Boiler feedwater (H_2O)	171
Primary steam (H_2O)	251
Reactor inlet (D_2O)	249
Reactor outlet (D_2O)	293
Cooling water rise	11.0
Pressure (MPa)	
Primary steam (H_2O) from steam generator	8.8
System pressure at reactor outlet header in heavy water loop	4.0
Condenser	0.005

The overall energy and exergy efficiencies are evaluated as for nuclear power generation, using Equations (20.1) and (20.2), respectively. Similar efficiency expressions are applied for most plant components except the condenser, which exists not to generate a product but rather to reject waste heat, making it difficult to define a "condenser efficiency." The reference-environment model in Table 6.1 is used, but with a temperature set at the approximate mean for the lake cooling water or 15°C. The following analysis simplifications are applied:

- The net heat produced by uranium is considered the main energy input. Also, the temperature at which heat can be produced by fissioning uranium is assumed theoretically so high that the energy and exergy of the heat can be considered equal. This assumption has a major effect on the exergy efficiencies discussed subsequently. If, alternatively, fission heat is at the temperature at which it is actually produced (i.e., the thermal neutron flux-weighted average temperature of about 880°C), the exergy of the heat is about 75% of the energy. Thus efficiency definitions for nuclear power generation used here follow nuclear industry conventions, but these efficiency definitions are inadequate because they are based on the heat released from the uranium rather than its energy or exergy content.
- All heat rejected by the moderator cooler is assumed produced in the moderator. The power utility actually reports that, of the 90 MW rate of heat rejection by the moderator cooler, 82 MW is produced in the moderator, 2.6 MW is transferred from

the fuel channel to the moderator, and 6.1 MW is produced in other reactor components (1.1 MW in the shield, 0.1 MW in the dump tank, 2.4 MW in the calandria and 2.5 MW in the calandria tubes) and transferred to the moderator (Ontario Hydro, 1985).

- D_2O is modeled as H_2O, thereby neglecting the chemical exergy of D_2O. This assumption is reasonable because the D_2O is in a closed loop and only transfers heat; only the D_2O physical exergy is of interest.
- The turbine isentropic and mechanical efficiencies are 80% and 95%, respectively.
- The generator and transformer efficiencies are both 99%, with heat losses from their surfaces occurring at 15°C.

23.1.1. Energy and Exergy Flows and Efficiencies

Energy and exergy flow rates are given in Table 23.1a for material flows and in Table 23.1b for electrical and thermal flows. Device exergy consumptions and their contributions to the overall plant exergy loss are provided in Table 23.3. Figures 23.2a and 23.2b illustrate the net energy and exergy flows and exergy consumptions for the four main process sections.

The distribution of outputs (electrical product and wastes) is shown in Figure 23.3 for energy and in Figure 23.4 for exergy. The latter figure also shows the loss associated with overall exergy consumption, which is broken down in Figure 23.5.

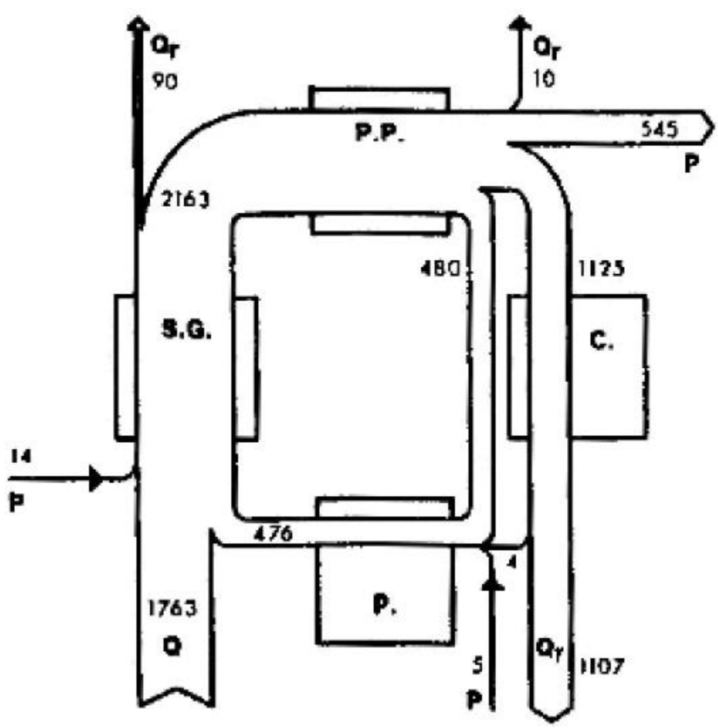

Figure 23.2a. Energy flow rates (in MW) through the four main sections of the nuclear power plant. Flow line thicknesses are proportional to the magnitude of the energy flow rate.

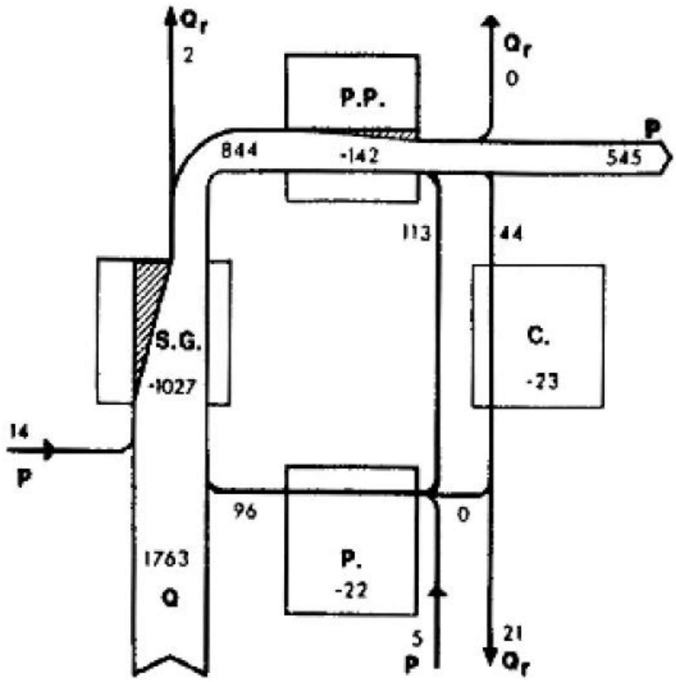

Figure 23.2b. Exergy flow rates (in MW) through the four main sections of the nuclear power plant. Flow line thicknesses are proportional to the magnitude of the exergy flow rate.

Table 23.3. Exergy consumption rates for nuclear power plant and its main sections and devices

Section	Device	Exergy consumption rate (MW)	% of total exergy loss rate
Steam generation	Reactor (including boiler)	969.7	78.4
	D_2O-H_2O heat exchanger	47.4	3.8
	D_2O pump	1.1	0.1
	Moderator cooler	9.0	0.7
	Total	1027.2	83.4
Power production	Turbines	116.6	9.4
	Generator and transformer	11.0	0.9
	Moisture separator and closed steam reheater	15.2	1.2
	Total	142.8	11.5
Condensation	Condenser	24.7	2.0
Preheat	Heat exchangers	19.8	1.6
	Pumps	0.5	0.0
	Total	20.8	1.7
Overall		1215.5	98.3

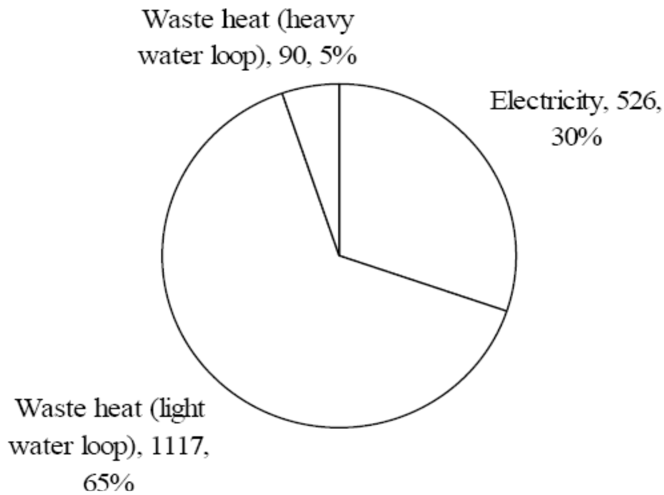

Figure 23.3. Distribution of energy outputs for the nuclear power plant, showing values in megawatts and as a percentage of the total output. Product and waste outputs are shown.

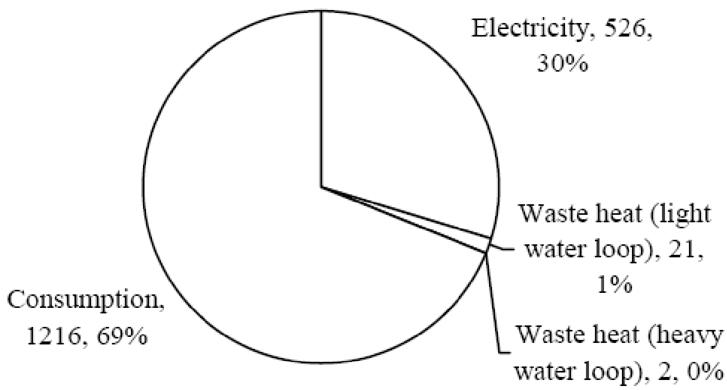

Figure 23.4. Distribution of exergy outputs (product and waste) and exergy consumption for the nuclear power plant, showing values in megawatts and as a percentage of the total output and consumption.

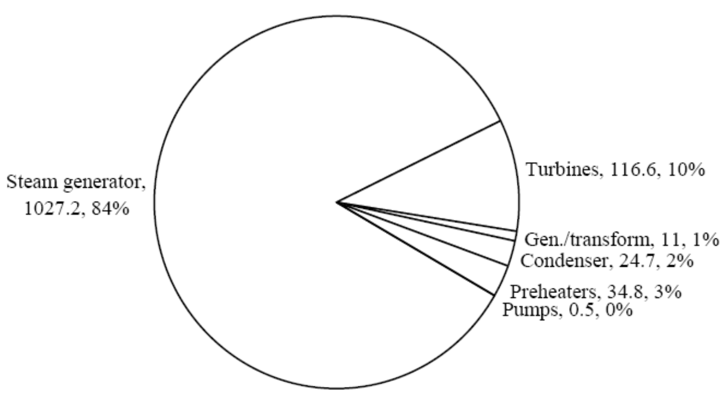

Figure 23.5. Breakdown by device of exergy consumptions for the nuclear power plant, showing values in megawatts and as a percentage of the total exergy consumption.

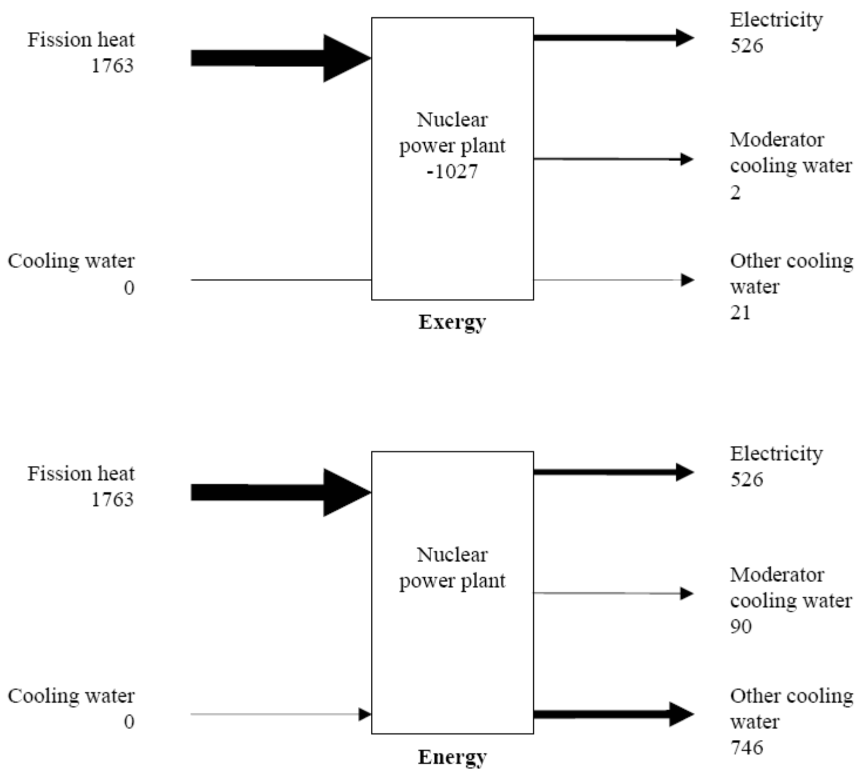

Figure 23.6. Overall exergy and energy balances for the nuclear power plant. The exergy balance shows flow rates and consumption rate (negative value in plant) of exergy (in MW), while the energy balance shows energy flow rates (in MW). In all balances, thicknesses of flow lines are proportional to the magnitude of the flow rate of the corresponding commodity.

An overall breakdown of the energy and exergy flows and exergy consumptions for the nuclear power plant is provided in Figure 23.6.

It is also noted that energy and exergy values and efficiencies for the overall process and its sections are in agreement with the literature for similar processes, and realistic variations in reference-environment properties do not significantly affect the energy and exergy results.

23.1.2. Interpretation of Energy and Exergy Efficiencies and Flows

Overall Plant

Overall energy and exergy efficiencies, where fission heat provides the only input energy or exergy, are the same:

$$\eta = \psi = \frac{(545 - 19)\,\mathrm{MW}}{1763\,\mathrm{MW}}(100\%) = 30\%$$

As shown subsequently, these efficiencies differ markedly for many station sections.

Preheating Section

Energy losses are minor in the preheating section (under 10 MW), as are exergy losses (about 20 MW). Internal consumptions comprise most of the exergy losses.

Steam Generation Section

Energy and exergy efficiencies for this section, considering the increase in energy or exergy of the water as the product, follow:

$$\eta = \frac{(2267 - 64 - 476)\ \mathrm{MW}}{(1763 + 14)\ \mathrm{MW}}(100\%) = 95\%$$

$$\psi = \frac{(862 - 18 - 96)\ \mathrm{MW}}{(1763 + 14)\ \mathrm{MW}}(100\%) = 42\%$$

The steam generation section is significantly more efficient based on energy than exergy, implying that although 95% of the input energy preheats water, the energy is degraded as it is transferred. Exergy analysis highlights this degradation.

Exergy consumptions in the steam generation section are substantial, accounting for 1027 MW or 83% of the total exergy losses (47 MW in the boiler, 9 MW in the moderator cooler, 1 MW in the heavy-water pump, and 970 MW in the reactor). The 970 MW exergy consumption rate in the reactor can be further understood by hypothetically breaking down the processes within it (Rosen, 2001):

- moderator heating (8% of the reactor exergy consumption),
- heating fuel pellets (to their approximate maximum temperature of 2000°C) (22%),
- transferring heat within fuel pellets to their surfaces (at approximately 400°C) (51%),
- transferring heat from the surface of the fuel pellets to the cladding surface (at 304°C) (8%), and
- transferring heat from the cladding surface to the primary coolant and then to the preheated boiler feedwater to produce steam (10%).

Power Production Section

In this section, energy losses are small (less than 10 MW total), and exergy losses are moderately small (around 150 MW). The exergy losses are mainly internal consumptions.

Condensation Section

In the condensers,

- a small quantity of exergy enters (44 MW for each unit), of which about 50% is rejected and 50% is internally consumed, and
- a large quantity of energy enters (1125 MW), of which close to 100% is rejected.

Thus, energy results erroneously suggest that almost all losses in electricity-generation potential are associated with condenser heat rejection, while exergy analyses demonstrate directly that the condensers are responsible for little of these losses (Figures 23.3-23.5). This discrepancy arises because condenser heat is rejected at nearly the environment temperature.

Exergy results show that the condenser waste is relatively insignificant for the process. The exergy rejected by the condensers is about 8% of the net exergy produced by the plant, while the energy rejected exceeds the net energy produced by approximately 140%.

23.1.3. Key Insights

Several illuminating insights are attained here about nuclear power generation:

- Energy losses are mainly in emissions (i.e., condenser heat rejection), and exergy losses are primarily with consumptions (mainly in steam generation).
- Although overall energy and exergy efficiencies are similar, energy analyses do not identify the locations and causes of inefficiencies, while exergy analyses do.
- Since devices with the largest thermodynamic losses have the greatest margins for efficiency improvement, efforts to increase the efficiencies of nuclear power generation should focus on the reactor. Technologies that generate electricity without degradation of nuclear fuel or utilize heat at high temperatures could increase efficiencies significantly.
- The use of heat rejected by condensers only increases the exergy efficiencies by a few per cent. Nuclear cogeneration systems, which produce heat at useful temperatures at the expense of reduced electrical output, can have greater efficiencies than conventional power generation, but the merit of cogeneration must be determined with exergy because energy analyses tend to overstate performance.

23.2. ENVIRONMENTAL IMPACT OF EXERGY LOSSES

The exergy-environment relations described earlier are illustrated for the 500-MW-capacity nuclear power station considered in the previous section:

- Order and resource degradation occur during the exergy consuming conversion of uranium to less ordered spent fuel. Although a degree of resource degradation is unavoidable for a real process, increased exergy efficiency can reduce the degradation. In the extreme, if the process in the example is made thermodynamically ideal by hypothetically increasing the exergy efficiency from 30% to 100%, uranium use and the related emissions decrease by about 70%. These insights are provided by exergy, but not energy. But this discussion neglects the energy and exergy of nuclear fuel.
- Waste exergy is associated with spent nuclear fuel, indicating simultaneously that it poses a potential risk to the environment but is also a source of useful energy. Societal concern regarding emissions of harmful chemical and radioactive constituents suggests that the potential for impact of these emissions is recognized, but not from the perspective provided by exergy. Also, waste exergy emitted with

waste heat to the atmosphere and lake represents a potential to impact the environment. Concern exists regarding thermal pollution in bodies of water, and exergy-based insights into environmental-impact potential of such phenomena could improve understanding.

- Chaos is created via the degradations described in the previous two bullets (i.e., resource degradation as fuel is used and surroundings degradation due to emissions). The degradation of fuel is apparent since the process products have less exergy than the inputs. The potential degradation of the environment due to waste emission exists if the emissions to the environment occur without constraint.

As pointed out earlier, exergy restricted in a system represents a resource, while exergy emitted to the environment in an unrestricted way represents a driving potential for environmental damage. This point is seen clearly by considering the spent nuclear fuel. Two benefits may result if this commodity is restricted rather than emitted to the environment: environmental damage is likely avoided, and the restricted waste becomes a potential source of exergy that is valued.

This illustration clearly demonstrates that exergy losses, whether in the form of exergy destruction or waste emissions, can affect the environment. Exergy destruction, in particular, can be used as a significant criterion for assessing the depletion of natural resources. Exergy analysis can help reduce resource use by indicating where the work potential or exergy of natural resources is lost. Furthermore, the exergy in a flow can only be entirely converted to products in a reversible process, i.e., one where exergy is neither destroyed nor emitted as waste. A reversible process is a theoretical ideal which we can seek but never realize. Real processes, which are irreversible, have exergy destructions and waste exergy emissions. Effort is often expended on reducing resource exergy destructions and waste exergy emissions, sometimes by converting them into by-products.

23.3. Inadequacy of Conventional Nuclear Power Plant Analyses in Technical and Environmental Assessments

As pointed out prior to Section 23.1.1, it is assumed here, following industry conventions, that the step in which heat is generated by fissioning uranium lies outside the nuclear reactor boundary. The energy and exergy efficiencies for the overall nuclear generating station and the steam generation section analyzed in the case study in the previous section are greatly affected by this assumption, rendering the results inadequate

23.3.1. What Are the Actual Resource Energy and Exergy?

It is not easy to determine the energy and exergy contents of fresh and nuclear fuel, and these values are not generally agreed upon. Assuming only fission technology, the energy and exergy values depend on the ultimate energy released via fission. But the true energy and exergy, relative to a reference environment, is far greater than the energy or exergy released during fission. In fact, it is generally recognized that only a small portion of the energy and exergy in nuclear fuel, often only a few percent, is utilized in fission reactors.

23.3.2. Impact on Technical and Environmental Assessments

Although based on nuclear industry conventions, the energy and exergy efficiency definitions are incomplete because they are based not on the energy or exergy content of the nuclear fuel, but instead only on the heat released from the uranium through fissioning.

The overall energy and exergy efficiencies for the case study would be significantly different if the nuclear fuel-to-fission heat step were considered. To perform a comprehensive analysis, the energy and exergy would be required for both the fresh and the spent nuclear fuel. Including the nuclear fuel-to-fission heat step would lead cause the results discussed the previous two main sections of this chapter to vary in several notable ways:

- The energy and exergy efficiencies of nuclear power generation would likely be less than 5%.
- The energy and exergy of spent nuclear fuel would be more clearly illuminated, since the potential of spent uranium is significant, as it is highly radioactive and releases significant quantities of heat for many years.
- The potential environmental impact associated with nuclear power generation waste would be highlighted, due to its high exergy content.

These factors impact exergy and energy performance and environmental and ecological impacts of nuclear power generation, and should be accounted for in improvement efforts.

Note that it is not unreasonable to suggest that nuclear power generation be assessed based not on fission heat but instead on the energy and exergy contents of the nuclear fuel. Such an approach simply parallels that used in fossil fuel based power generation, where we generally evaluate efficiencies based on the energy and exergy contents of the fuel, not on the amount of heat that can be delivered by their combustion.

23.4. Closing Remarks

The energy and exergy analyses performed of nuclear power generation, as well as the assessment of the environmental and ecological impacts of the process, demonstrate the enhanced understanding yielded through exergy analysis into

- the thermodynamic performance of the process, including a clearer picture of efficiencies, losses, areas with significant potential for improvement,
- resource degradation, and
- environmental and ecological impacts.

Incomplete perspectives are obtained with the industry convention of carrying out assessments on the basis of fission heat input, rather than the energy and exergy values of fresh and spent nuclear fuel.

Chapter 24

BIOFUELS PROCESSING

OVERVIEW

The renewability of a biofuel is examined quantitatively using an exergy-based approach that incorporates a renewability indicator as well as the concepts of non-renewable resource consumption and restoration work. The approach is used to assess the renewability of producing the biofuel ethanol from corn. It is demonstrated that exergy may be produced through natural thermochemical cycles driven by solar energy and that biofuel renewability depends on various factors (e.g., biomass, biofuel production, regional conditions). The case study of ethanol production from corn is determined to be non-renewable, but it is also shown that for different cases biofuels can be renewable.

The exergy-based approach for renewability quantification using a renewability indicator, described in Section 10.8, is applied to biofuels in this chapter. The case study examined is the production of the biofuel ethanol from corn. To support the analysis, biofuels are described and the renewability of a biofuel is examined generally. This chapter draws extensively on an earlier publication (Berthiaume et al., 2001).

24.1. BIOFUELS

The exploitation of biomass-derived fuels, or biofuels, as renewable energy sources can be considered as the harnessing of solar energy through a natural thermochemical cycle.

Biofuels are different than many renewable energy resources since the time scale for their production and consumption is much shorter than for other energy sources like fossil fuels.

Biofuels are often viewed as renewable energy sources and thus considered less polluting than many other energy sources. This understanding has led to significant interest in them. Nonetheless, biofuels can have environmental impacts, e.g., many biofuels are based on intensive agriculture.

There are many biofuels, and many biomass substances can be used to product biofuels. Also, many processes for converting biomass to biofuels exist.

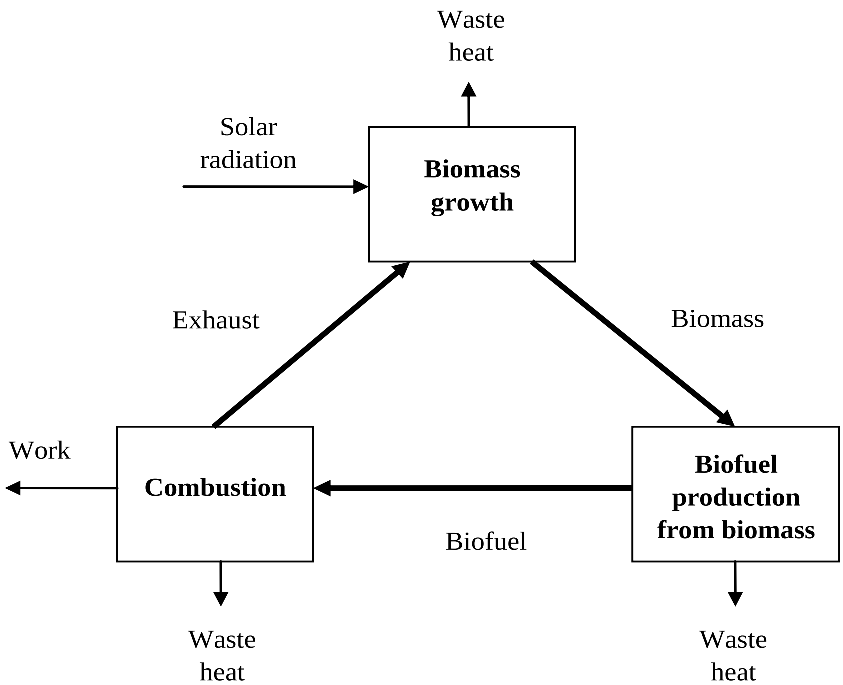

Figure 24.1. Potentially renewable cycle for biofuel from biomass. Heavy lines denote material flows, and light lines energy flows.

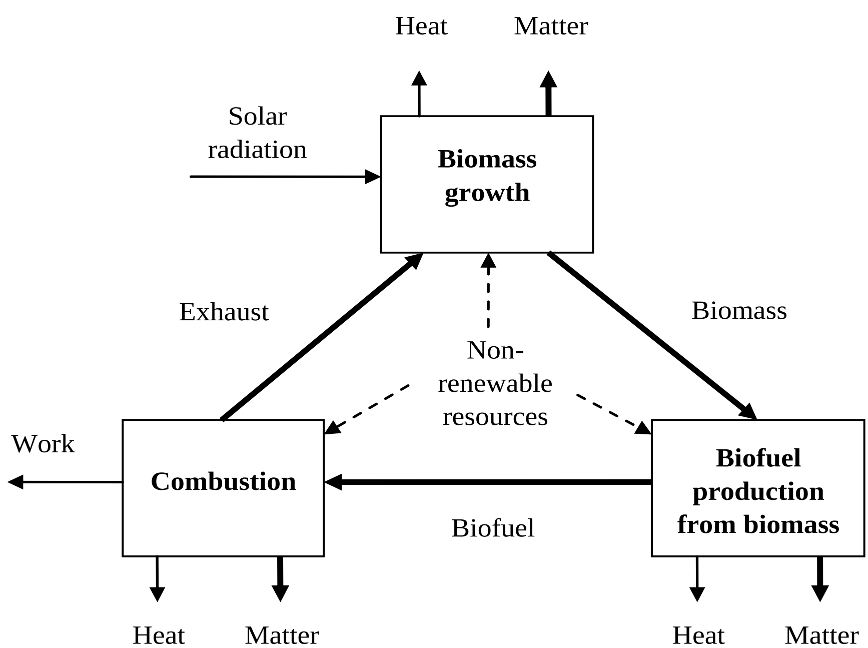

Figure 24.2. Non-renewable cycle for biofuel from biomass, in which non-renewable resources are consumed in driving the natural cycles and in waste treatment. Heavy lines denote material flows, and light lines energy flows. Dashed lines can be either, as they denote non-renewable resources. The heat and matter emitted from each process are normally wastes.

24.2. Biofuel Renewability

A potentially renewable cycle biomass production cycle is illustrated in Figure 24.1. The net effect of the cycle is work production from solar radiation. Non-renewable resources (NRRs) are not utilized during the cycle. The cycle has no material wastes because it is closed, but waste heat exits.

In practice, NRRs are normally consumed in harnessing natural cycles and in the treatment of ensuing wastes, and material wastes exit (see Figure 24.2). This NRR consumption should be taken into account in establishing the extent to which a resource is renewable. The discrepancies between ideal and actual behavior play a key role in evaluating biofuel renewability. These discrepancies can be analyzed from an exergy perspective.

24.3. Ethanol Production from Corn

24.3.1. Theoretical Cycle

The common way to produce ethanol from corn, one biomass production process, involves the cyclic transformations of carbon according to the following simplified processes:

- Corn is naturally grown from water, atmospheric CO_2 and solar radiation. The main chemical reaction is the photosynthesis of glucose from carbon dioxide:

$$6CO_2 + 6H_2O + \text{solar radiation} \rightarrow C_6H_{12}O_6 + 6O_2 + \text{heat} \tag{24.1}$$

- The glucose in corn is converted to ethanol, via the following reaction:

$$C_6H_{12}O_6 + [6O_2] \rightarrow 2C_2H_5OH + 2CO_2 + [6O_2] + \text{heat} \tag{24.2}$$

- The ethanol is combusted to produce work, yielding CO_2, via the following reaction:

$$2C_2H_5OH + [2CO_2] + 6O_2 \rightarrow 4CO_2 + [2CO_2] + 6H_2O + \text{heat} \tag{24.3}$$

The components in brackets in Equations (24.2) and (24.3) do not take part in the reaction at the defined step. These chemical reactions together constitute a complete thermochemical cycle where solar radiation is converted into usable heat while matter (carbon dioxide, water, oxygen, ethanol, glucose) is cycled.

24.3.2. Actual Cycle

A typical production cycle for ethanol from corn is shown in Figure 24.3. Corn is grown on farms, using artificial fertilizers and pesticides as well as lime for soil pH adjustment, and farming machinery, which consumes diesel fuel. The corn is harvested and dried, using heat from propane combustion. The dried corn is crushed and fermented in water. The resulting ethanol solution is filtered and purified using distillation. The product pure ethanol can be used as a fuel for automobiles or for other purposes. As a biofuel, the ethanol produces work, as well as CO_2 and other combustion products. The cycle then repeats.

We consider here data for ethanol processing from the United States, and for corn production and drying from agricultural practices in Quebec, Canada.

The time span for the completion of a cycle is considered to be one year since in Quebec there is only one harvest per year. In the overall process, 2.6 kg of corn is required to produce 1 L of ethanol (USDA, 1980). The NRRs used for corn production are shown in Table 24.1. The NRRs for corn conversion to ethanol are all energy resources, specifically 0.48 MJ of electricity and 16.7 MJ of fuel (assumed diesel fuel for exergy analysis), per liter of ethanol produced (Pimentel, 1991).

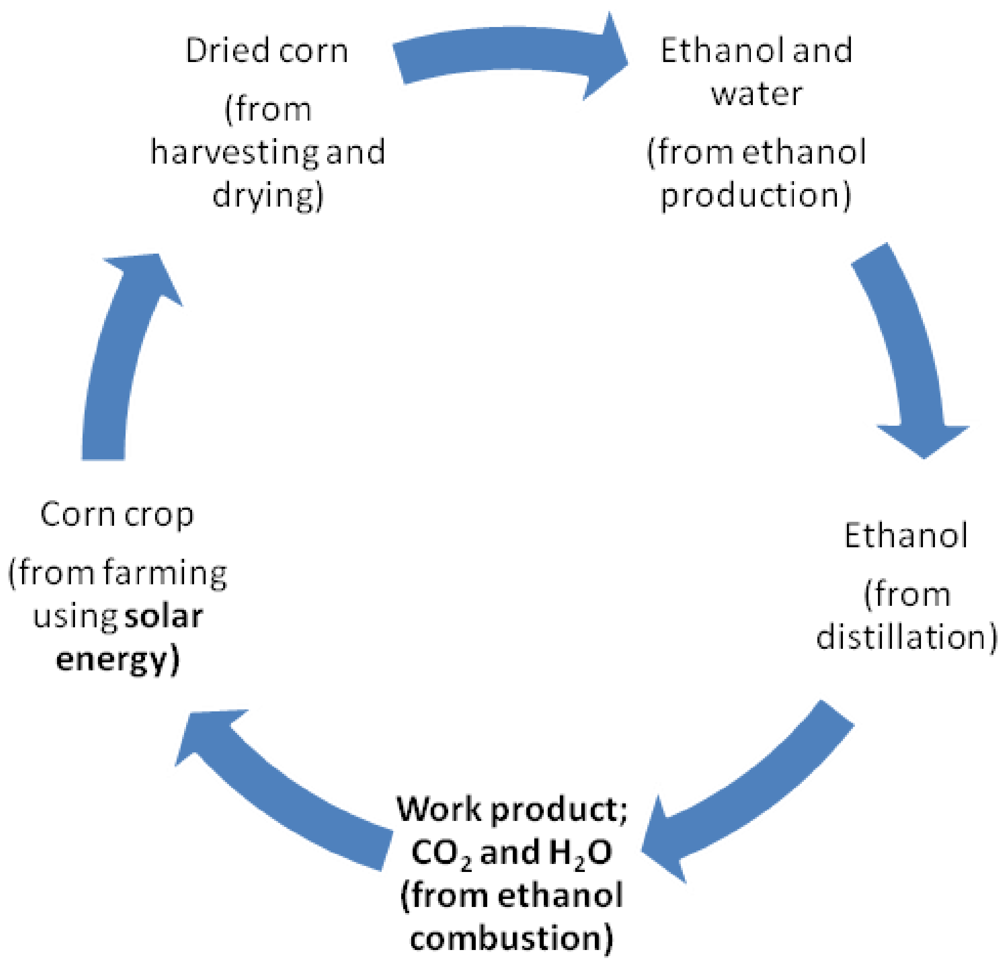

Figure 24.3. Principal steps in cycle for converting corn to the biofuel ethanol, with main external input (solar energy) and output (work product) highlighted. The ethanol production step includes crushing of dried corn and fermentation.

Table 24.1. Resource consumption for corn production (per hectare of land area)

Resource category	Resource	Purpose	Quantity*
Energy	Diesel fuel	Machine fuel	71 L
	Propane	Drying of corn	252 L
	Electricity	General use	475 MJ
Fertilizer	Phosphorus	Fertilizer	55 kg
	Nitrogen	Fertilizer	150 kg
	Potassium	Fertilizer	85 kg
Land treatment	Lime	pH adjustment	270 kg

* Data sources by resource category: Larochelle et al. (1977) for energy, CPV (1994) for fertilizer, and Tisdale et al. (1985) for land treatment.

For simplicity, all matter except NRRs is considered recycled in the process. Thus water and carbon are fully recycled within the system, so the parts of hydrosphere, lithosphere and atmosphere that act as water and carbon reservoirs are included in the system. The cycling flows and transformations of carbon and water for the corn-to-ethanol process are as follows:

- *Carbon cycle*. On an annual and per hectare of land area basis, the primary production from CO_2 is 6330 kg of corn (BSQ, 1992) and 8000 kg of stalk, leaves and roots (Tran, 1995), while corn processing produces 2450 L of ethanol and 2000 kg of dry distiller grain (an organic solid waste) and 7840 kg of biochemical oxygen demand (BOD) in the wastewater (USDA, 1980; Pimentel, 1991). When corn is cultivated in a monoculture with tillage, 2000 kg/ha/year of organic matter (humus) is lost from the soil (Michaud, 1995), mainly due to soil oxidation and erosion (Tabi et al., 1990). This lost organic matter is considered to be transformed to CO_2 ultimately and returned to the atmosphere. To compensate for this loss, 2000 kg/ha/year of organic matter must be returned to the soil. Michaud (1995) states that composting in the field of the 8000 kg of stalk, leaves and roots remaining from the corn culture allows approximately 1600 kg of organic matter to be recycled into the soil. Assuming the same ratio for the composting of dry distiller grain, an additional 400 kg of organic matter may be returned to the soil which globally should compensate for the humus lost during corn culture. The organic solid waste from wastewater treatment is much smaller, but can also be composted.
- *Water cycle*. The cycling of water is taken to be fully renewable, as water for corn growth is assumed provided only by rain, with no artificial irrigation. Part of this water is returned to the atmosphere by plant evapotranspiration and part is stored in the corn, stalk, leaves and roots. Water vapor is emitted during the drying of corn and ethanol combustion. The crushed corn is mixed with water for fermentation, but distillation subsequently separates this water from the fermentation product.

Water pollution is a potential issue with the cycle. During corn farming, some fertilizers and pesticides leach out from the corn field into local water. The pesticide mainly used for corn agriculture in Quebec is atrazine. The volume of polluted water and the pollution extent are based on data for the specific case of the Chibouet River, which is in the corn production region in Quebec. For each hectare of cultivated corn and for each crop season, 1500 m^3 of water is estimated to be contaminated with an average concentration of 5 μg/L of atrazine (Giroux et al., 1997; Gangbazo and Babin, 2000). The processing of corn to ethanol generates wastewater which must be treated before disposal via release to the environment. The production of one liter of ethanol is considered here to generate 160 liters of wastewater with an average BOD concentration of 20 g/L (Pimentel, 1991).

24.4. Exergy Analysis of Ethanol Production from Corn

The specific chemical exergies of the components in Equations (24.1) to (24.3) are listed in Table 24.2, based on values reported by Szargut et al. (1988). For glucose and ethanol, the chemical exergy values reflect the exergy needed to synthesize these compounds from the reference elements. For O_2 and CO_2, the values reflect the concentration differences between the pure species and its concentration in the reference environment. The exergy of these gases correspond to the compression work for the species from the gas at its atmospheric pressure to the reference-environment pressure (1 atm). The exergy of H_2O is not shown in Table 24.2.

The values in Table 24.2 can be used to evaluate the chemical exergy of matter at various points in the cycle (see Table 24.3). Exergy is accumulated in matter through photosynthesis and then released during ethanol production and combustion.

The process can be considered from renewable and non-renewable perspectives:

- When viewed as renewable, this process behaves like that in Figure 24.1 (with corn as the biomass and ethanol as the biofuel). The maximum work that can be produced from ethanol combustion is 2,659,740 kJ/kmol of glucose, i.e., the difference in the exergies in Table 24.3 after steps 2 and 3. Such a potentially renewable device would produce work without disturbing the environment composition because the cycling matter would be confined. Also, the thermal impact of this device would be zero if the waste heat were rejected at the reference-environment temperature and ultimately transferred to space. Thus, this device can theoretically behave renewably, i.e., utilize renewable energy without impacting the environment.
- When viewed as non-renewable, the process behaves that in Figure 24.2 (with corn biomass, ethanol biofuel, biofuel growth via farming, and biofuel production including fermentation, distillation and other processes). NRRs are consumed in the processes in the cycle and in the treatment of generated wastes. This NRR consumption helps establish the extent to which a resource is renewable, as it highlights the difference between the ideal and actual behavior of the biofuel process.

Table 24.2. Specific chemical exergies of chemical species involved in the ethanol cycle

Component	State	Specific chemical exergy* (kJ/kmol)
Ethanol, C_2H_5OH	Liquid	1,357,700
Glucose, $C_6H_{12}O_6$	Solid	2,928,800
Carbon dioxide, CO_2	Gas	19,980
Oxygen, O_2	Gas	3,970

* Data source: Szargut et al. (1988).

Table 24.3. Breakdown by step of exergy of materials in ethanol cycle (for 1 kmol glucose in cycle)

Step	Exergy of materials after step (kJ)
Photosynthesis of glucose from carbon dioxide	2,952,620
Ethanol production from glucose	2,778,960
Ethanol combustion	119,220

24.5. EXERGY-BASED RENEWABILITY OF ETHANOL PRODUCTION FROM CORN

An energy flow diagram for the corn-to-ethanol process is similar to the general biofuel production energy flow diagram in Figure 10.2. The corn-to-ethanol cycle includes the ethanol production cycle as well as waste treatment processes. Work and heat are produced from solar radiation and NRRs are degraded, becoming wastes. Some of the wastes are recycled in the process. Part of the produced work (equal to the restoration work) is used to regenerate the non-recycled NRRs to their initial states. The produced and restoration works are now evaluated and utilized to evaluate the renewability indicator for the overall process.

24.5.1. Work Production for Ethanol Production from Corn

The corn-to-ethanol cycle is harnessed to produce work W_p, assumed produced via ethanol combustion in an engine. With current technology, the exergy efficiency of the cycle, defined as the percentage of the chemical exergy of ethanol converted to work, is 34.5% (Gallo and Milanez, 1992). Thus, the produced work is 7.9 MJ per liter of ethanol, or 19,355 MJ on the basis of one hectare of corn field.

24.5.2. Restoration Work for Ethanol Production from Corn

The restoration work is based on the non-renewable resource consumption associated with four main processes:

- *Electricity production*. Electricity is generated hydroelectrically and from fossil fuels in Quebec. Hydroelectric generation exploits the natural water cycle driven by solar energy and is thus considered totally renewable. But NRRs (e.g., steel, concrete, fuel) are consumed for dam construction and materials, and the net exergy consumption for these materials, based on data from several sources (Szargut et al., 1988; Berthiaume and Bouchard, 1999; SEBJ, 1987), is 357 x 10^8 MJ (Berthiaume et al., 2001). Over a 50-year period these considerations give a $CNEx_p$ value of 0.006 MJ per MJ of generated hydroelectricity. Note that this CNEx value is not comprehensive, as it does not account for local electricity distribution, maintenance of the distribution system, and some elements of environment restoration (e.g., the impact of the submerging of land and the mercury released into reservoirs). For fossil fuel-based electricity generation, CExC = 4.17 MJ per MJ of electricity (Szargut et al., 1988). Given 95% of electricity is generated hydroelectrically and 5% from fossil fuel combustion in Quebec, the overall cumulative net exergy consumption is CNEx = 0.2142 MJ per MJ of electricity.

- *Corn production and conversion to ethanol*. NRR consumption in corn production and ethanol processing is given earlier (Section 24.3.2 and Table 24.1) on the basis of one hectare of corn field, while the specific CNEx and restoration work associated with each NRR consumption are shown in Table 24.4. The annual restoration work is 86,059 MJ for corn production and conversion to ethanol on the basis of one hectare of corn field. This value is the sum of five contributing values: 1) for nitrogen, ammonium nitrate (CExC = 32.7 MJ/kg (Szargut et al., 1988)) is considered and, since 150 kg/ha of nitrogen (N) is used to fertilize the soil (CPV, 1994) and ammonium nitrate is 35% nitrogen, 428.6 kg of ammonium nitrate is needed per hectare, leading to an annual restoration work for nitrate use of 14,015 MJ per hectare; 2) for phosphorus, 70 kg/ha is needed in the form of P_2O_5 (CPV, 1994) (CNEx = 5.58 MJ/Kg (Wittmus et al., 1975; Szargut et al., 1988)), giving an annual restoration work for phosphorus of 391 MJ/hectare; 3) for potassium, 90 kg of K_2O is needed per hectare (CPV, 1994) and the energy requirement to produce K_2O is 7.7 MJ/kg (Pimentel, 1991), leading to a restoration work of 693 MJ/ha; 3) 1.8 kg of lime (CExC = 5.67 MJ/kg (Szargut et al., 1988)) is needed per kilogram of nitrogen use to neutralize the acidity resulting from nitrogen application (Tisdale et al., 1985), so 270 kg of lime per hectare is needed and the restoration work is 1530 MJ/ha; 4) 71 liters of diesel fuel (specific gravity = 0.84 and CExC = 53.2 MJ/kg) is needed in the process (Larochelle et al., 1977), leading to a restoration work for diesel fuel of 3173 MJ/ha; and 5) 252 L of propane (specific gravity = 0.508 and CExC = 61.6 MJ/kg (Szargut et al., 1988)) is used to dry the corn (Tisdale et al., 1985), so 128 kg of propane is used per hectare and the restoration work is 7886 MJ per hectare.
- *Wastewater from ethanol processing*. Wastewater from ethanol processing is assumed to enter the municipal sewer system and the industrial/domestic wastewater mix is treated in a biological municipal wastewater station. For municipal wastewater treatment in Quebec, the average electricity consumption is 4.13 kWh per kg of BOD removal (Blais et al., 1995). Since 160 liters of wastewater with an average BOD concentration of 20 g/L (Pimentel, 1991) needs to be treated for each liter of ethanol, the electricity consumption for wastewater treatment is 13.2 kWh (or 47.5 MJ) of electricity per liter of ethanol. For a CNEx of 0.2142 MJ per MJ of electricity, CNEx is 10.17 MJ per liter of ethanol or 24,927 MJ per hectare of corn field per year.
- *Polluted water treatment*. The Chibouet River, which flows through Quebec where corn is intensively produced, is considered. The watershed area of the Chibouet River is 150 km^2 (Gangbazo and Babin, 2000), of which 36% is used for corn production (Giroux et al., 1997). For each crop season and each hectare of cultivated corn, 1500 m^3 of water is contaminated with the pesticide atrazine with an average concentration of 5 μg/L (Giroux et al., 1997). Kruithof et al. (1995) show that pesticides may be separated from water by reverse osmosis and, assuming reverse osmosis requires water pressurization to 1.4 MPa, the separation work is estimated at 2100 MJ per

hectare of cultivated corn per year. If the water pumps are driven by electric motors with efficiencies of 65%, the CNEx for water treatment is 692 MJ per hectare of cultivated corn per year.

Although the restoration work for polluted water treatment is based here on the exergy consumption for existing treatment, it is noted that the restoration work for polluted water treatment can be estimated as the theoretical minimum separation work, as described in Chapter 16. An efficiency factor usually needs to be applied, as this minimum work is much less than the actual energy used in water treatment facilities.

The total restoration work for all the above steps are summed in Table 24.4, showing the restoration work to be 111,678 MJ for the overall process.

24.5.3. Renewability Indicator for Ethanol Production from Corn

On an annual hectare basis, the work produced W_p in the corn-to-ethanol process is 19,355 MJ and the corresponding work of restoration W_R is 111,678 MJ. From Equation (10.3), the renewability indicator I_r is evaluated as –4.77.

This value of the renewability indicator implies that case considered for the production of the biofuel ethanol from corn is not renewable. All the work produced is needed to restore the environment, and additional work is needed to restore completely the degraded NRRs. By providing such insights, the renewability indicator is demonstrated to be a useful quantitative tool for environmental and technological decision making.

Table 24.4. Non-renewable resource use and restoration work (per hectare of corn)

Process	Non-renewable resource (NRR) parameters			Restoration
	Type	CNEx*	Quantity used	work, W_R (MJ)
Corn farming	Diesel fuel	53.2 MJ/kg	59.6 kg	3,171
	Phosphorus (P_2O_5)	7.52 MJ/kg	55 kg (P)	391
	Nitrogen (NH_4NO_3)	32.7 MJ/kg	150 kg (N)	14,015
	Potassium (K_2O)	4.56 MJ/kg	85 kg (K)	693
	Lime (Burnt)	5.67 MJ/kg	270 kg	1,530
	Propane	61.6 MJ/kg	128 kg	7,886
	NRR for electricity	0.2142 MJ/MJ	475 MJ	102
Corn-ethanol conversion	Diesel fuel	53.2 MJ/kg	40,915 MJ	49,507
	NRR for electricity	0.2142 MJ/MJ	40,915 MJ	8,764
Wastewater treatment	NRR for electricity	0.2142 MJ/MJ	116,375 MJ	24,927
Polluted water treatment	NRR for electricity	0.2142 MJ/MJ	3,231 MJ	692
All				111,678

* Data sources for CNEx: Szargut et al. (1988) for diesel fuel, nitrogen, lime and propane, Wittmus et al. (1975) for phosphorus, and Pimentel (1991) for potassium.

Generalizations about the renewability of biofuel conversion cannot be drawn from the value of the renewability indicator found for this case study, as the renewability indicator is case dependent. The value of the renewability indicator is significantly affected by many factors: resources, technology, location, environmental constraints and considerations (e.g., land use, toxicology, social factors), and sustainable management strategies.

The significance of two key factors on the renewability indicator is described below:

- *Electricity mix*. The renewability and NRR use for electricity utilization depends highly on the mix used of energy sources and conversion processes. For the present case study, the mix for Quebec is applied (95% hydroelectric and 5% fossil fuel). But the electricity mix varies by country and region. If electricity is entirely generated thermally from fossil fuels, the CNEx associated with electricity becomes 4.17 MJ per MJ of electricity (Szargut et al., 1988) which yields $I_r = -37.7$. This renewability indicator value is much lower than the value of –4.77 obtained in this case study, implying the process is less renewable when fossil fuel-derived electricity is used.
- *Wastewater treatment*. The wastewater treatment method used also affects significantly the renewability of for ethanol production from corn. An anthropogenic system like activated sludge or aerated lagoons is considered in this case study. But if a natural system like wetlands is used for wastewater treatment, the NRR degradation for wastewater treatment is eliminated and $I_r = -3.48$, indicating that the process is closer to renewability.

The renewability indicator can be applied to resources other than biofuels and various production processes.

24.6. CLOSING REMARKS

Biofuels are described and the renewability of a biofuel is examined quantitatively using an exergy-based approach. The renewability indicator in the approach incorporates the concepts of non-renewable resource consumption and restoration work. It is demonstrated that exergy can potentially be produced through natural thermochemical cycles driven by solar energy and that biofuel renewability depends on various factors (e.g., processes for producing the biofuel, biomass, regional conditions). For the case study assessed, production of the biofuel ethanol from corn, the process is determined to be non-renewable since a negative value is obtained for the renewability indicator. But the approach also indicates that the process could be modified to be renewable for ethanol or other biofuels, demonstrating the usefulness of the exergy-based approach to assessing resource renewability.

Chapter 25

HYDROGEN PRODUCTION

OVERVIEW

The environmental implications of hydrogen production and use are examined from an exergy perspective for two case studies involving thermochemical water decomposition using the copper-chlorine cycle driven by nuclear thermal energy (although solar thermal energy is also a possible driver). In the first case study, exergetic life cycle assessment is applied, considering the three main process steps (uranium processing, nuclear plant operation and hydrogen production) and four environmental impact categories (acidification, eutrophication, global warming and ozone depletion potential). In the second case study, EXCEM analysis is applied, so as to attain an enhanced understanding of technical, environmental and economic performance.

The need to improve the efficiency of energy utilization and to develop environmentally benign energy systems has motivated work to develop technologies to support hydrogen as an alternative energy carrier, which complements electricity and which can facilitate reductions in utilization of fossil fuels and emissions of CO_2 and other greenhouse gases. Hydrogen energy can help in achieving such benefits by allowing nuclear, solar and wind energy to be used to produce hydrogen from water. In this chapter, two exergy-based environmental methods, exergetic life cycle analysis and EXCEM analysis, are applied to hydrogen production from energy sources other than fossil fuels.

25.1. HYDROGEN PRODUCTION PROCESSES

Many experts predict that society’s energy systems will transform in the future to a “hydrogen economy,” in which the main energy carriers are electricity and hydrogen. These energy carriers are synergistic, with each having advantages in meeting the needs of people and societies for energy services.

Hydrogen gas is not available as a resource in abundant quantities in the environment. Rather it must be produced from other resources. Normally hydrocarbons or water are reacted to yield hydrogen, which must be separated from the reaction products.

25.1.1. Hydrocarbon-Based Hydrogen Production

Most of the hydrogen used today is produced from fossil fuels, primarily via steam reforming of natural gas, because it is economically advantageous compared to other production processes. Coal gasification is also used to produce hydrogen. Hydrogen production from such carbon compounds will likely remain the main production method in the near future. A particularly significant concern with hydrogen production from fossil fuels is that such processes emit carbon dioxide and thus contribute to climate change, so their use may become limited in the longer term.

25.1.2. Non-Hydrocarbon-Based Hydrogen Production

Most proponents of a hydrogen economy suggest that the hydrogen will ultimately be produced from water using non-fossil energy resources. Two important drivers are environmental concerns and diminishing fossil fuel reserves. Non-hydrocarbon-based processes obtain hydrogen through the following reaction:

$$2H_2O \rightarrow 2H_2 + O_2 \tag{25.1}$$

Many processes for producing hydrogen from resources other than hydrocarbons exist or are being investigated. Some important options for hydrogen production from non-fossil energy resources, from the perspective of having achieved a degree of commercial success or nearing the commercialization stage, are now described.

Water Electrolysis

This electrochemical process is commercial and produces hydrogen from electricity and water. The water is provided as a liquid for low-temperature electrolysis and as steam for high-temperature electrolysis. The process is not driven by fossil fuels provided it utilizes non-fossil electricity. The overall efficiency for hydrogen production via water electrolysis is dependent on the efficiencies of both water electrolysis, which is highly efficient, often having values of about 80%, and electricity generation. For thermal power generation, advanced technologies are expected to achieve energy efficiencies of up to 60%, although conventional power plants of the present day normally exhibit energy efficiencies of about 35%. Water electrolysis is the preferred non-hydrocarbon production option and is likely to remain so in the near term.

Thermochemical Water Decomposition

Hydrogen can be produced primarily from thermal energy and water using thermochemical cycles (Figure 25.1) (Funk, 2001; Rosen, 2010). Such cycles consist of a sequence of chemical reactions, for which the net reaction is water decomposition (see Equation (25.1)). Many combinations of chemical reactions have been investigated that separate water into hydrogen and oxygen in a closed cycle, but it remains uncertain which thermochemical processes will ultimately prove the most feasible and economic. Thermochemical hydrogen production avoids the inefficiency associated with thermal electricity generation by utilizing the thermal energy directly in the thermochemical cycle. Thermochemical water decomposition is expected to achieve an energy efficiency of up to 50%, and is considered by many as a likely future process for large-scale hydrogen production from thermal energy derived from nuclear and/or solar energy.

Note that water decomposition is achieved using indirect thermochemical cycles, rather than direct thermal processes, because the former permit operation at relatively low temperatures (500-900°C). For example, heat is required at about 500°C for the copper-chlorine process and at about 900°C for the sulfur-oxygen-iodine process. Both these temperatures are much lower than the very high temperatures of about 2500°C required to produce appreciable amounts of hydrogen and oxygen by direct thermal decomposition of water (Serban et al., 2010).

The temperature of the thermal energy for hydrogen production, whether provided by nuclear, solar or other resources, must be compatible with that required by the production process. A high-temperature nuclear reactor or a concentrating solar thermal collector can serve as the heat source for thermochemical decomposition of water. Several advanced nuclear reactor technologies under consideration for integration with thermochemical cycles for hydrogen production follow: super-critical water cooled reactor (SCWR), high-temperature gas-cooled reactor (HTGR), advanced gas reactor (AGR), advanced high-temperature reactor (AHTR), and modular helium reactor (MHR). For instance, the SCWR with a peak temperature of about 550°C is suitable for use with the copper-chlorine thermochemical cycle (Granovskii et al., 2008; Mokry et al., 2009) and is being developed by several countries, e.g., it is being considered as Canada's Generation IV nuclear reactor.

Hybrid Water Decomposition Cycles

Hybrid processes combine the above two types of processes for hydrogen production (see Figure 25.2). These thermochemical and electrochemical processes are driven by electricity and heat, and are under development. Thermochemical and hybrid methods may become more important and economic in the future, especially if electricity becomes significantly more expensive than process heat. For example, estimates from Japan suggest that the cost of nuclear thermochemical hydrogen production could be as low as 60% of that for nuclear hydrogen production by water electrolysis.

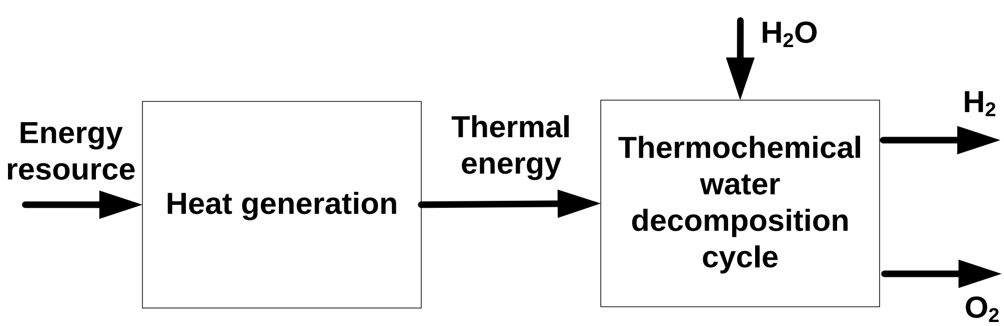

Figure 25.1. Thermochemical water decomposition process for hydrogen production from thermal energy, which has been generated from a resource.

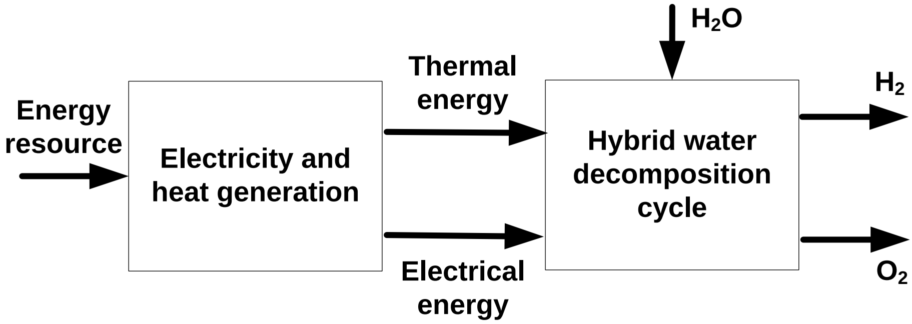

Figure 25.2. Hybrid (electrochemical and thermochemical) water decomposition process for hydrogen production from thermal and electrical energy, which have been generated from a resource.

25.1.3. Copper-Chlorine Cycle for Thermochemical Water Decomposition

One possible version of the copper-chlorine (Cu-Cl) thermochemical water decomposition process is illustrated in Figure 25.3, which shows the various intermediate copper and chlorine compounds involved in the cycle. The cycle consists of three chemical reactions and one electrochemical reaction, and involves five steps:

1. *HCl production*. $CuCl_2$ reacts with water to produce HCl (g) and $CuOCuCl_2$ at a temperature of around 450ºC in a fluidized bed.
2. *Oxygen production*. Oxygen and CuCl are produced by splitting $CuOCuCl_2$.
3. *Copper production*. Copper (Cu) is produced from molten CuCl, at a reaction temperature as low as around 25ºC, using electricity.
4. *Drying*. Aqueous $CuCl_2$ is dried to solid $CuCl_2$ which is used in HCl production.
5. *Hydrogen production*. Solid copper particles from the copper production step react exothermically at 450ºC with HCl from the HCl production step, yielding hydrogen gas and CuCl.

Each step except the fourth involves a chemical reaction. The chemical reactions form a closed internal loop that decomposes water while recycling the copper-chlorine compounds and emitting to the atmosphere no greenhouse gases or other substances.

The super-critical water cooled reactor is viewed as particularly suitable for integrating with the Cu-Cl thermochemical cycle.

Hydrogen production costs for Cu-Cl thermochemical cycles having various hydrogen production capacities are shown in Table 25.1, based on costs reported in a previous economic assessment (Orhan et al., 2008, 2010; Naterer et al., 2009). Hydrogen production is observed to be more economic at larger production capacities. The cost for this process for a daily of capacity 200 tons hydrogen can be broken down as follows: 40% for energy, 29% for the hydrogen production plant, 29% for hydrogen distribution and 3% for hydrogen storage.

Table 25.1. Cost of hydrogen production from thermochemical water decomposition plants based on the Cu-Cl cycle, for several hydrogen production capacities*

Cost	Hydrogen production capacity (ton/day)			
	2	10	50	200
Unit capital cost ($/GJ)				
Hydrogen production	13.2	7.7	4.4	2.7
Hydrogen storage	0.5	0.5	0.5	0.5
Unit operating cost ($/GJ)				
Energy	6.3	6.3	6.3	6.3
Distribution	4.6	4.6	4.6	4.6
Total unit cost				
Energy basis ($/GJ)**	24.6	19.1	15.8	14.1
Mass basis ($/kg)	3.49	2.71	2.24	2.00

* Modified from (Orhan et al., 2008; Naterer et al., 2009).

** Each total unit cost on an energy basis in the second last row is the sum of the unit costs in the previous rows.

25.2. ExLCA of Nuclear-Based Hydrogen Production via Thermochemical Water Decomposition

Exergetic life cycle analysis is employed for evaluating the environmental impact associated with the life cycle of hydrogen production. A life cycle approach is important because the oxidation of hydrogen emits mainly water and thus makes the usage stage appear misleadingly clean by neglecting environmental impacts during hydrogen production. ExLCA is illustrated here through a case study involving of nuclear-based hydrogen production via thermochemical water splitting using a copper-chlorine (Cu-Cl) cycle.

25.2.1. System Description

A simplified life cycle for nuclear-based hydrogen production via thermochemical water splitting is shown in Figure 25.4. The system has three main subsystems:

- *Fuel processing*. Facilities include mining, milling, conversion, enrichment of uranium ore and fabrication of nuclear fuel in the form of UO_2.
- *Nuclear plant*. Electrical and thermal energy are produced from nuclear fuel in a supercritical water cooled nuclear reactor. The SCWR is expected to operate at sufficiently high temperatures and pressures to integrate with thermochemical water decomposition using the five-step copper-chlorine cycle (Naterer et al., 2009, 2010; Rosen et al., 2012). The electrical requirement of each of the processes is supplied by the electrical output from the nuclear power plant, and excess electricity is exported.
- *Hydrogen production plant*. Hydrogen is produced from water using thermal and electrical energy, via thermochemical water decomposition using the five-step copper-chlorine cycle.

25.2.2. Mass and Energy Considerations

Normalized material and energy inputs and outputs (per kg H_2 production) are shown in Table 25.2 for thermochemical water decomposition using the five-step Cu-Cl cycle. The determination of these values for each plant section follows:

- *Hydrogen production plant*. The thermal energy required obyf the hydrogen production process is evaluated following Wang et al. (2010). Per mole of hydrogen production, the cycle external heat input is 391.4 kJ, evaluated noting that the heat input is 554.7 kJ, the total heat output is 232.0 kJ, and the recovered heat is 163.3 kJ (assuming 70% heat recovery, focused on low grade heat). Also, the electrical energy requirement, per mole of hydrogen production, is 62.6 kJ for the copper production step and 38 kJ for auxiliary equipment. The total thermal energy requirement is 195.7 MJ/kg H_2 and the total electrical energy requirement is 50.3 MJ/kg H_2.
- *Nuclear power plant*. The thermal energy output of the nuclear plant meets the thermal energy requirement for the Cu-Cl cycle, while the electrical energy output of the nuclear plant satisfies the electrical energy requirements of the hydrogen production plant, uranium mining, heavy water production, etc. The mass of nuclear fuel needed to obtain the required thermal energy is evaluated as the ratio of heat produced to discharge burn-up (Solli, 2004; Pioro and Duffey, 2007).
- *Fuel processing*. To produce 1 kg of 4% enriched uranium, 9.02 kg natural uranium is needed, so to obtain the 0.404 g of enriched uranium in Table 25.2, 3.64 g of natural uranium is input for enrichment and 7.29 g of uranium ore is required.

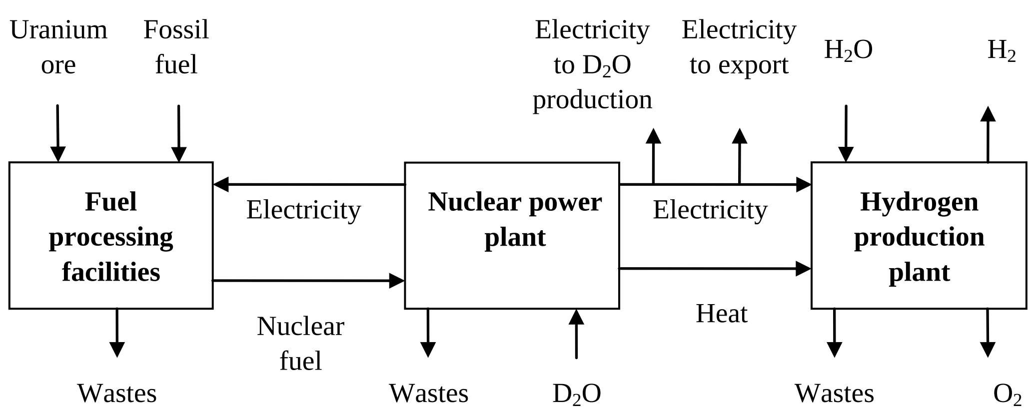

Figure 25.4. Simplified life cycle of nuclear-based hydrogen production via thermochemical water splitting, showing the main flows. The nuclear power and hydrogen production plants include operating and construction phases. A heavy water production facility supplies heavy water to the nuclear plant.

Table 25.2. Normalized external flows (per kg hydrogen production) for nuclear and hydrogen plants using the five-step Cu-Cl cycle

Flow direction	Flow type	Flow	Plant	
			Nuclear (SCWR)	Hydrogen production
Input	Material (g)	Water		9000
		Uranium	0.404	
	Energy (MJ)	Heat		195.7
		Electricity		50.3
Output	Material (g)	Hydrogen		1000
		Oxygen		8000
	Energy (MJ)	Electricity	313.1	
		Reactor heat	195.7	
		Waste energy	195.7	

Table 25.3. Normalized exergy consumptions (per kg hydrogen production) and exergy efficiencies for the life cycle of nuclear-based hydrogen production

System	Normalized exergy consumption (MJ)	Exergy efficiency (%)
Fuel processing	2916.3	26.7
Nuclear plant	673.8	36.4
Hydrogen production plant	8.6	93.2

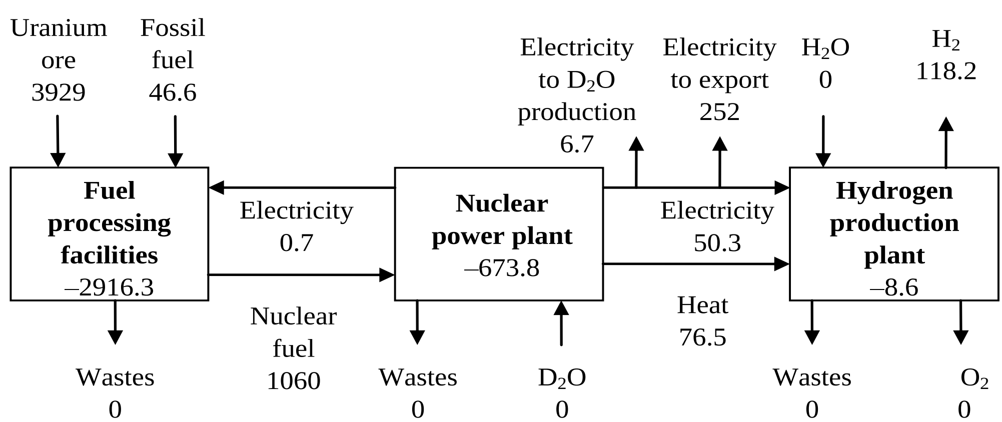

Figure 25.5. Exergy flow diagram for the life cycle of nuclear-based hydrogen production, normalized to 1 kg hydrogen production. Positive values are normalized exergy flows, and negative values are normalized exergy consumptions.

25.2.3. Exergy Considerations

A normalized exergy flow diagram of the life cycle of the process for nuclear-based hydrogen production is presented in Figure 25.5, based on one kg of hydrogen production. Normalized exergy destructions and exergy efficiencies, evaluated with Equation (5.7), are shown in Table 25.3. For 1 kg of hydrogen production, the exergy of H_2 is 118.2 MJ, the electrical energy requirement of the hydrogen plant is 50.3 MJ, the exergy of the heat input to the hydrogen plant is 76.5 MJ, the exergy content of enriched uranium is 1060 MJ, the exergy input with uranium ore to fuel processing is 3929 MJ, and the chemical exergy of the fossil fuels (coal, natural gas and diesel fuel) used in fuel processing total 46.6 MJ.

25.2.4. Environmental Analysis with ExLCA

The overall environmental impacts are determined for subsystems in Figure 25.4. LCA is applied using the GaBi 4 LCA software and data from numerous sources (Solli, 2004; Lubis et al., 2010; Ozbilen et al., 2012. For simplicity, a black-box approach is used for the ExLCA and a simplified mass balance is employed. A 50 year plant lifetime is assumed, and two industrial-scale hydrogen production capacities are considered.

Environmental impacts for hydrogen production by thermochemical water decomposition using the five-step Cu-Cl thermochemical cycle, normalized to 1 MJ exergy of hydrogen production, are listed in Table 25.4 for four CML 2001 impact categories:

- Global warming potential (GWP) due to anthropogenic emissions, which increases the Earth's surface temperature and leads to climate change.
- Ozone depletion potential (ODP) in the stratospheric ozone layer due to ozone-depleting emissions.
- Acidification potential (AP) associated with the deposition of acidifying pollutants on soil, groundwater, surface waters, biological organisms, ecosystems and materials.
- Eutrophication potential (EP) from excessive levels of macronutrient emissions.

The values for the four impact measures are higher for the smaller hydrogen production capacity. The ozone depletion potential is mainly attributable to utilization of the nuclear plant and mining. The values are somewhat sensitive to plant lifetime, with the values increasing or decreasing by about 10% when the lifetime is shortened or lengthened by 20 years, respectively, from the lifetime of 50 years assumed here.

The ExLCA results are observed by combining the LCA data in Table 25.4 with the exergy flow, destruction and efficiency data in Figure 25.5 and Table 25.2.

Table 25.4. Selected normalized environmental impact measures (per 1 MJ exergy of hydrogen) for five-step Cu-Cl thermochemical cycle for hydrogen production

Impact category	H_2 production capacity (kg per day)	
	62,500	125,000
Global warming potential, GWP (g CO_2-eq)	5.86	5.75
Ozone depletion potential, ODP (g R11-eq)	1.24×10^{-7}	1.22×10^{-7}
Acidification potential, AP (g SO2-eq)	0.0297	0.0292
Eutrophication potential, EP (kg Phosphate-eq)	0.00242	0.00238

Table 25.5. Variation of normalized global warming and acidification potentials with hydrogen plant exergy efficiency, on basis of 1 MJ exergy of hydrogen

Impact category	H_2 plant efficiency (%)		
	88	93	98
Global warming potential, GWP (g CO_2-eq)	6.1	5.8	5.4
Acidification potential, AP (g SO2-eq)	0.031	0.029	0.027

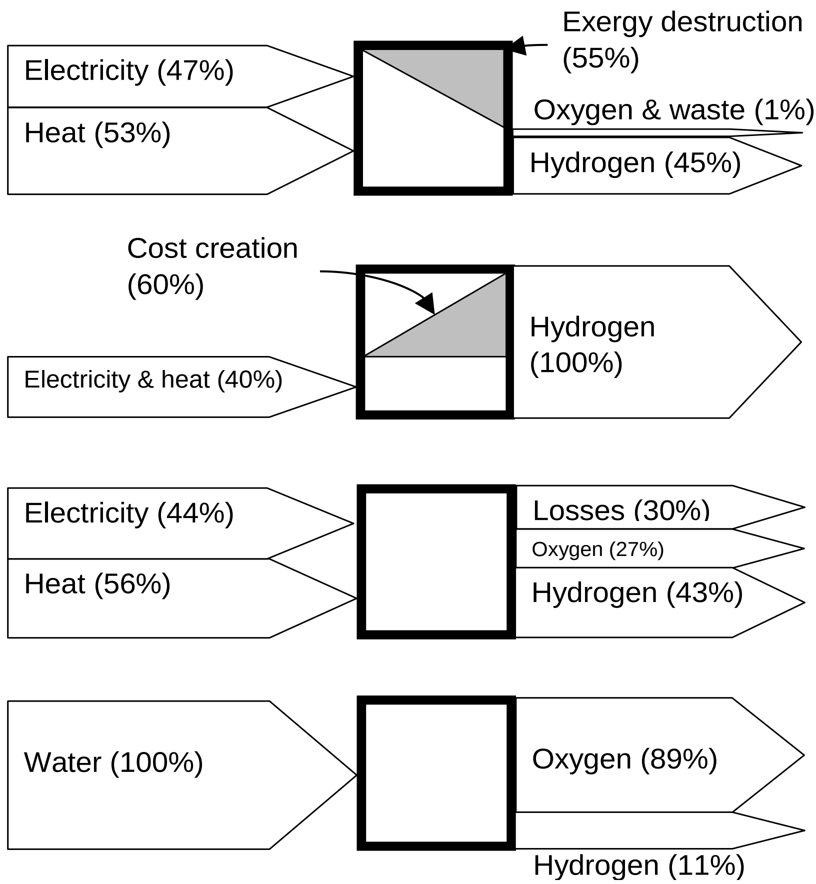

Figure 25.6. Normalized EXCEM flow diagram for hydrogen production by Cu-Cl thermochemical water decomposition (denoted by box in center of each diagram): exergy (row 1), cost (row 2), energy (row 3) and mass (row 4). Line thicknesses for flows are proportional to the corresponding magnitudes, and the non-conservation of exergy and cost are designated by shaded regions. Inputs of exergy, energy and mass are normalized to 100% of total input, and other values are relative. Cost output is normalized to 100% and other costs are relative. Cost output is assigned to the product hydrogen.

The primary contributor of the life cycle irreversibility of nuclear-based hydrogen production is fuel (uranium) processing, for which the normalized exergy destruction is 2916.3 MJ and the exergy efficiency is 26.7%. The next highest contributor is nuclear plant operations, which exhibit a lower normalized exergy destruction (673.8 MJ) and a greater exergy efficiency (36.4%). The hydrogen plant contributes the least to life cycle irreversibility, exhibiting the lowest normalized exergy destruction (8.6 MJ) and the highest exergy efficiency (93.2%).

The variation with hydrogen plant exergy efficiency is shown in Table 25.5 for two environmental impact measures: global warming and acidification potentials. From the base values for a hydrogen plant exergy efficiency of 93%, GWP and AP both vary nearly linearly with plant exergy efficiency. A 5% increase in the hydrogen plant efficiency reduces GWP and AP by about 5-7%, while a 5% decrease in the hydrogen plant efficiency increases GWP and AP by about 5-7%. If a high exergy efficiency target of 98% is set, the normalized GWP can potentially be reduced to 5.4 g CO_2-eq and the normalized AP to 027 g SO_2-eq, per MJ exergy of hydrogen. Table 25.5 highlights the importance of heat recovery in the cycle, since improved heat recovery increases the hydrogen plant exergy efficiency.

25.3. EXCEM Analysis of Hydrogen Production via Thermochemical Water Decomposition

An understanding of the potential technical, environmental and economic performance of the Cu-Cl thermochemical water decomposition cycle for hydrogen production is required to facilitate the development of a clean and viable design, and subsequent optimization. Exergy methods for thermochemical water decomposition have been reviewed recently by Rosen (2008, 2010). An EXCEM assessment can provide for the cycle useful insights on the relations between environmental impact and EXCEM quantities. An EXCEM assessment for thermochemical water decomposition using the copper-chlorine cycle is summarized in Figure 25.6. The assessment focuses on environmental implications and considers on the relations involving exergy losses (internal exergy consumptions and waste exergy emissions).

25.3.1. Analysis of EXCEM Quantities

Mass

A mass rate balance for the overall Cu-Cl cycle is shown in Figure 25.6 (bottom row), where only external inputs and outputs are shown (i.e., excluding compounds cycling within the internal closed loop). Water enters the cycle and hydrogen and oxygen exit after the water is decomposed. Hydrogen accounts for 11% of total mass input rate and oxygen 89%.

Hydrogen is the primary product. Oxygen can be treated as a waste or a by-product. The latter is often the case due to its purity and the existence of numerous markets for it.

Energy

An energy rate balance for the overall Cu-Cl cycle is shown in Figure 25.6 (third from top), where it is evident that the Cu-Cl cycle is a hybrid cycle driven by both heat and electricity. The figure provides several insights:

- The energy efficiency for this hydrogen production process, considering only hydrogen as the product, is 43%.
- 44% of the input energy is provided by electricity and 56% by heat.

- Hydrogen accounts for 43% of total energy flow rate, oxygen 27% and waste heat emissions 30%. The energy of the oxygen is mainly physical rather than chemical, and is relatively large because of its high temperature exiting the cycle.

Exergy

An exergy rate balance for the overall Cu-Cl cycle is shown in Figure 25.6 (top row), where it is evident that exergy is not conserved. Several other observations can be made:

- The exergy efficiency of the cycle (45%) slightly exceeds the energy efficiency.
- The main exergy loss is associated with exergy destruction, although waste exergy emissions also occur but are relatively minor.
- The exergy of the hydrogen and oxygen outputs is much less than the exergy of the thermal and electrical energy inputs.
- The exergy content of the hydrogen is much greater than that of the oxygen, even though the mass flow rate of the oxygen greatly exceeds that of the hydrogen. This observation can be explained by the differences in their chemical exergies: the molar chemical exergy is 236,090 kJ/kmol for hydrogen but only 3970 kJ/kmol for oxygen.
- Electricity makes up a greater portion of the input on an exergy basis than on an energy basis, because the exergy of the heat is much less than its energy.

Cost

A cost rate balance for the overall Cu-Cl cycle is shown in Figure 25.6 (second row from top), where it is seen that the cost rate of the input energy (heat and electricity) combined with the levelized capital and processing cost rate of the plant is accounted for in the output cost rates. Two key observations can be made:

- The cost creation rate is significant, accounting for 60% of the total cost output rate. Like exergy, cost is clearly not conserved during the process, but cost increases, unlike exergy which is destroyed due to irreversibilities.
- The output cost is allocated to the hydrogen product, treating the oxygen as a waste and neglecting its potential as a saleable commodity. Although this allocation of input and created cost rates is reflected in Figure 25.6 (second row from top), this assignment is subjective and can be altered to permit a non-zero oxygen cost rate.

Summary

Flow rates of several EXCEM quantities for a Cu-Cl thermochemical hydrogen production plant with a daily capacity of 50 tons are shown in Figure 25.7. The quantities represented in Figure 25.7 are energy and exergy flow rates and unit costs on a mass basis, and are taken from prior assessments. The levelized plant costs are greater than the input thermal and electrical energy costs, and the exergy destruction rate, the difference of all exergy input and out rates, is 0.05 GW.

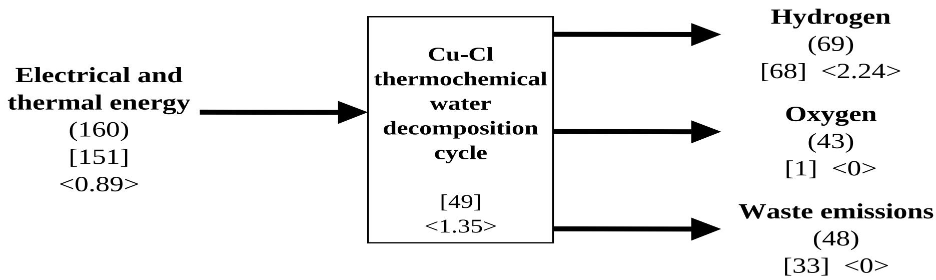

Figure 25.7. Flow rates of three EXCEM quantities for hydrogen production using a Cu-Cl cycle for thermochemical water decomposition, based on a plant with a capacity of 50 tons/day hydrogen. Values attached to flows in parentheses denote energy flow rates (in MW), in square brackets denote exergy flow rates (in MW), and in angle brackets denote normalized cost flow rates (in $/kg). Values within the system in square brackets denote exergy consumption rate (in MW) and in angle brackets denote normalized cost creation rate (in $/kg). Although oxygen is attributed no cost in this figure, it could be treated as a by-product and assigned a cost.

25.3.2. Environmental, ecological and economic implications

It is informative to compare and contrast the EXCEM quantities assessed in the previous subsection, to obtain further insights and understanding about the Cu-Cl thermochemical hydrogen production cycle, in terms of environmental and ecological impact as well as economics. To help illustrate these points, relations between several important EXCEM quantities are shown for the cycle.

The variation with the plant cost creation rate of the exergy loss rate (for waste emissions) and the exergy destruction rate for the Cu-Cl thermochemical hydrogen production cycle is shown in Figure 25.8. The contribution of losses in the form of internal consumptions and external waste emissions is clearly visible, indicating that both need to be addressed to reduce environmental and ecological impact.

The variation with cost creation rate of the energy loss from the cycle with heat and oxygen is presented in Figure 25.9. The oxygen curve is shown separately because it can be treated as a waste or a by-product. Figure 25.9 suggests that it is sensible to perform costing based on exergy rather than energy for several reasons. First, the exergy losses measure the actual deviation of efficiency from ideality, making them more meaningful than the energy losses. Second, the exergy values provide a more consistent measure of value, with large exergy quantities associated with valuable commodities. Third, the energy values only sometimes represent a measure of value.

The relations of the exergy loss rates with cost creation rate described in this section demonstrate the trade-off between cost and efficiency. Efficiency approaches the ideal (i.e., total exergy loss approaches zero) if an increasingly large investment is made, while the total exergy input is wasted (i.e., total exergy loss approaches the total exergy input) if no investment is made. The enhanced understanding of the relations between environmental, ecological, economic and thermodynamic factors for hydrogen production using a Cu-Cl thermochemical cycle provided by EXCEM analysis can aid efforts by designers to reduce environmental and ecological impacts and to enhance economics, and therefore may assist efforts to improve and optimize the cycle, as it is developed towards commercialization.

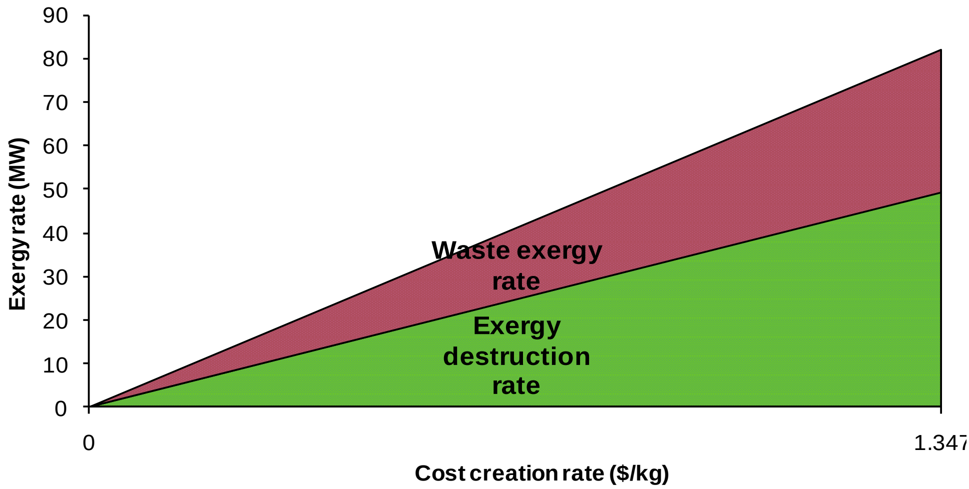

Figure 25.8. Variation of overall exergy loss rate (top curve) with cost creation rate for the Cu-Cl thermochemical water decomposition cycle for hydrogen production, and contributions to the overall exergy loss rate by waste exergy emission rate and exergy destruction rate.

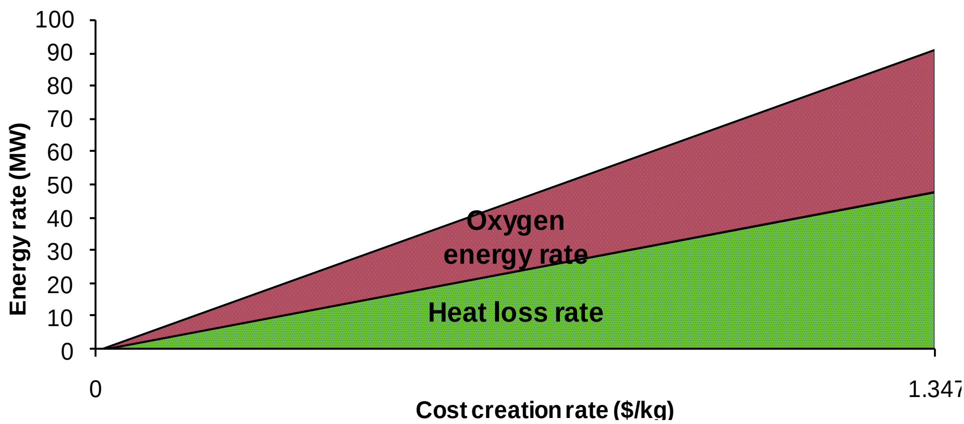

Figure 25.9. Variation of overall energy loss rate (top curve) with cost creation rate for the Cu-Cl thermochemical water decomposition cycle for hydrogen production, and contributions to the overall energy loss rate by heat loss rate and energy emission rate with oxygen

25.4. Closing Remarks

Environmental and ecological implications of hydrogen production are described from an exergy perspective through two case studies that conisder the Cu-Cl thermochemical water decomposition cycle driven by nuclear thermal energy (and possibly solar thermal energy in the future): an exergetic life cycle assessment and an EXCEM analysis. The ExLCA, which considers the three main process steps (uranium processing, nuclear plant operation and hydrogen production) and four environmental impacts (acidification, eutrophication, global warming and ozone depletion) reveals that the greatest life cycle irreversibility is caused by uranium processing. The EXCEM analysis provides an enhanced understanding of the technical, environmental and economic performance of the process.

Chapter 26

AUTOMOTIVE OPERATIONS

OVERVIEW

Three case studies for automotive operations are considered that apply the notions that exergy represents a type of potential of an emission to impact the environment and that life cycle considerations are required for a comprehensive assessment of the environmental and ecological impact. In the first case study, operating emissions are examined from two alternate automobile power trains: a methanol-fueled spark ignition engine and a hydrogen-fueled fuel cell. In the second case study, emissions produced for 13 fuel life cycles for automobiles are examined and compared on mass and exergy bases. In the third case study, a detailed exergetic life cycle assessment is presented of four vehicle technologies (including renewable energy options and internal combustion engines and hydrogen fuel cells). The case studies demonstrate that exergy-based methodologies for assessing qualitatively and quantitatively the potential for environmental impact are both promising and likely to assist in the development and design of more environmentally benign automotive technologies.

Three case studies for automotive operations are considered in order to illustrate that exergy is in some ways a measure of the potential of the substance to impact the environment and that life cycle considerations are required comprehensively assess the environmental and ecological impact of processes. Conventional and advanced vehicle technologies are considered, as are conventional and alternative fuels. The first case study focuses on the operating emissions from two alternate automobile power trains (methanol-fueled spark ignition engines and hydrogen-fueled fuel cells). The second case study extends the first by examining the life cycle emissions produced for 13 automobile and fuel combinations, on mass and exergy bases. The third case study extends the second by providing a detailed exergetic life cycle assessment of four vehicle technologies.

26.1. EXERGY OF AUTOMOBILE EMISSIONS

The transportation sector is a major source of potentially harmful waste emissions. In the United States, for example, that sector accounts for 26% of the total greenhouse gas, 77% of carbon monoxide and 49% of nitrogen oxides emissions (EPA, 1998a, 1998b). Interest in reducing dependence on fossil fuels and developing more environmentally benign modes of transportation has fostered the development of alternative fuel and vehicle technologies.

Based on the idea that the exergy of emissions represents a potential measure for environmental damage, the exergy of emissions from two power train technologies for automobiles are compared in this section: a spark ignition (SI) engine fueled with methanol and a fuel cell operated using hydrogen and air. The exergy values are normalized on a per unit of shaft work output basis to include the effect of conversion efficiency.

26.1.1. Description of Systems and Operating Data

The methanol-fueled spark ignition engine and hydrogen/air fuel cell are described. An arbitrary energy service of 10 kWh is selected in order to compare the exergy of emissions.

Methanol-fueled Spark Ignition Engine

The fuel consumption for the methanol-fueled spark ignition engine considered is 15.0 liters methanol/100 km, which is equivalent to 7.6 liters gasoline/100 km, and the corresponding emissions are 0.60 g/km for CO, 0.15 g/km for NO_x and 0.10 g/km for HC (Menrad et al., 1988).These data are based tests carried out on a passenger car according to a standard duty cycle outlined in the Federal Test Procedure (Menrad et al., 1988). Engine operating conditions are set at a compression ratio of 12.5 and a stoichiometric air/fuel ratio. A three-way catalyst is used for emission control. All hydrocarbons in the exhaust are taken to be in the form of unburned fuel, which is reasonable since 85% of the hydrocarbons are found in tests to be methanol (Menrad et al., 1988), and nitrogen oxide emissions are assumed to be 75% NO and 25% NO_2. The power train associated with the internal combustion engine (ICE), including the transmission, is assumed to have an energy efficiency of 15% to 25%.

Hydrogen/Air Fuel Cell

The solid polymer hydrogen/air fuel cell considered was developed at Ballard Power Systems, and operates at a temperature of 80°C and a pressure of 3 atm. Fuel cell emissions are calculated assuming steady state operation with 50% excess air. The fuel cell exhaust is water vapor (Prater, 1990). The power train associated with the fuel cell, including the fuel cell and motor, is assumed to have an energy efficiency between 35% and 45%.

26.1.2. Methodology

Chemical exergy is assessed here. Physical exergy is not considered because it appears not to contribute significantly to environmental impact, i.e., thermal emissions are virtually benign and high pressure emissions are unusual. Thus, if exergy is to be used as an indicator of potential for environmental impact for automotive applications, then the chemical exergy component effectively becomes that indicator, suggesting that an emission with greater chemical exergy has greater potential for environmental impact. The impact on the environment is a function of the processes which bring a material into equilibrium in the environment. In this section, exergy efficiency is utilized, defined as the percentage of product exergy output per unit of exergy input to a device or process.

26.1.3. Relevant Exergy Values and Their Determination

We consider waste emissions produced during the fuel life cycle for automotive vehicles, and the chemical part of exergy. The specific chemical exergy of a substance in the reference environment can be written as

$$ex^{ch} = RT_o \ln(P_o/P_{oo}) \tag{26.1}$$

where R is the universal gas constant, and P_{oo} is the partial pressure of the component in the reference state. Substances not found in the reference environment develop work as they react with substances in the reference environment to form substances that are found in the reference environment. In such cases, the specific chemical exergy is given by

$$ex^{ch} = -\Delta G_o - (\sum x_i ex_i^{ch})_{in} + (\sum x_i ex_i^{ch})_{out} \tag{26.2}$$

where subscripts in and out denote inputs and outputs, respectively, and G_o is the Gibbs function of formation, which can be written as

$$G_o = (v_k g_k)_{products} - (v_j g_j)_{reactants} \tag{26.3}$$

Here, v_k *and* v_j are the stoichiometric coefficients, g_k *and* g_j are the molar Gibbs functions of formation, and j denotes the jth co-reactant and k the kth product. *T*he chemical exergy for constituent i of a mixture can be expressed as

$$ex_i^{ch} = x_i ex_i^{ch} + RT_o x_i \, ln \, x_i \tag{26.4}$$

The reference environment used corresponds to that in Table 6.1, but with a pressure of 0.1 MPa to be consistent with the JANAF thermochemical properties (Chase Jr., 1998), from which some thermodynamic data are obtained.

26.1.4. Exergy of Emissions

The exhaust for the spark ignition engine consists of the products of methanol combustion in air, and for the fuel cell consists of water and other components of air (see Table 26.1). Chemical exergy can be broken down into concentration and reactive components. Emissions from the hydrogen/air fuel cell vehicle consist of components of air which do not participate in any reaction and water vapor from the oxidation of hydrogen, which provides the energy output. The chemical exergy of the substances exhausted is due to differing concentrations of these substances from the reference-environment concentrations. Although water vapor is naturally occurring in the environment, its emission has exergy because of its high concentration compared to that in the reference environment.

Table 26.1. Composition of exhaust gas for the energy conversion technologies

Exhaust constituent	Mole fraction	
	Methanol-fueled spark ignition engine	Hydrogen/air fuel cell
N_2	0.6206	0.6663
H_2O	0.2522	0.2656
O_2	0	0.0597
CO_2	0.1046	0.0003
CO	0.0093	0
Ar	0.0076	0.0081
CH_3OH	0.0036	0
NO	0.0016	0
NO_2	0.0005	0

Table 26.2. Comparison of fuel and exhaust chemical exergies

Energy conversion technology	Fuel chemical exergy		Emission chemical exergy		
	kJ/kg	kJ/kmol	kJ/kg fuel	kJ/kmol fuel	% of fuel chemical exergy
Hydrogen fuel cell	116,774	235,276	2,150	4,331	1.84
Methanol SI engine	22,500	720,901	834	26,736	3.71

Table 26.3. Fuel and emission data for a fixed energy service of 10 kWh*

Device	Power train efficiency (%)	Inputs		Outputs	
		Specific energy required	Specific fuel consumption (g/kJ)	Specific chemical exergy of emissions	Specific water produced (g/kJ)
Fuel cell	40	2.50	0.0214	0.0460	0.1914
Spark ignition engine	20	5.00	0.2222	0.1854	0.2499

* Here “specific” means per unit of shaft work.

Emissions for the methanol-fueled spark ignition engine consist of some components whose chemical exergy is based on concentration and some whose chemical exergy is based on reactions in the reference environment. The main combustion products, CO_2 and H_2O, have chemical exergies due to a concentration difference. Exhaust components like NO, NO_2, CO and CH_3OH, because they are not found in the reference environment, react there.

The chemical exergy of the two fuels, and the chemical exergy of emissions resulting from their use with corresponding energy conversion technologies, are compared in Table 26.2. As a percentage of fuel exergy, the exergy of emissions from the hydrogen-fueled fuel cell is about half that for the methanol-fueled spark ignition engine.

The exergy of emissions from each fuel and energy conversion technology pair are shown Table 26.3 for an energy service of 10 kWh. The mass of fuel required to provide that energy service is determined using typical power train efficiencies. The mass of hydrogen required is more than an order of magnitude less than the mass of methanol required, which is not surprising given the high energy density of hydrogen per unit mass. Water is produced by both methanol and hydrogen oxidation but, for the same energy service, the fuel cell power train generally produces less water. With the fuel cell power train operating at low efficiency and the combustion engine power train operating at high efficiency, the masses of water exhausted are comparable. The chemical exergy of emissions for the combustion engine is observed in Table 26.3 to be greater than that for the fuel cell, considering a typical range of efficiencies for each power train.

The effect of power train efficiency on the chemical exergy of emissions is illustrated in Figure 26.1 for both energy conversion technologies, based on a parametric study. The emission chemical exergy for the methanol-fueled spark ignition engine is seen to be more sensitive to variations in power train efficiency than the hydrogen/air fuel cell. But for all efficiencies considered, the chemical exergy of emissions for the methanol-fueled spark ignition engine exceeds that for the fuel cell.

26.1.5. Environmental Interpretations

It is generally perceived that emissions from a spark ignition engine have greater potential for environmental impact than those from a solid polymer fuel cell. It is shown here that the exergy of emissions from the engine are greater than those from the fuel cell, supporting the notion that chemical exergy of emissions may be a parameter with which environmental impact can be in part judged. Of course chemical exergy is one of many possible criteria and is not be a complete criterion because it does not account for factors like residence time, and specific interactions with the biosphere and health impacts.

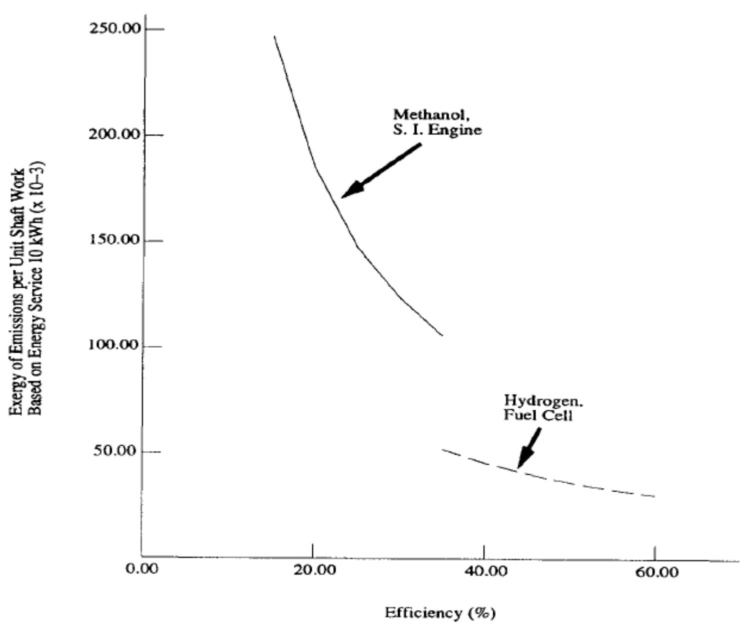

Figure 26.1. Chemical exergy of emissions as a function of power train efficiency, shown over the efficiency range for each power train.

Emissions have the ability to cause change as they react in and diffuse through the environment. This analysis demonstrates that the emissions from a power train based on a spark ignition engine fueled with methanol are more out of equilibrium with the environment than those from a power train based on a fuel cell fueled with hydrogen, for a common energy service provided. The fact that the fuel cell power train converts fuel into an energy service more efficiently than the combustion engine power train amplifies the difference in magnitude of the exergy of emissions.

26.1.6. Extension to Gasoline Spark-Ignition Engines and Other Emissions

Methanol and hydrogen may be seen as competing to succeed gasoline in some efforts to reduce the pollutants from the transportation sector, so it is useful to consider how the results of this section extend to a gasoline engine. The chemical exergy of emissions from a methanol-fueled engine and a gasoline (or octane)-fueled engine would probably not differ dramatically. Both power trains would have comparable efficiencies. Methanol, with a lower carbon-to-hydrogen ratio than gasoline, would likely yield emissions having lower exergy due to decreased carbon dioxide concentration and slightly higher conversion efficiency.

26.2. COMPARATIVE EXERGY-BASED ENVIRONMENTAL ASSESSMENT OF LIFE CYCLE EMISSIONS FOR AUTOMOBILES AND FUELS

Examining and contrasting the emissions produced during the full life cycle of a fuel improves understanding of the environment impact of vehicles and fuels. Concentrating only on emissions during vehicle operation, rather than the life cycle, can be misleading, e.g., suggesting erroneously that electric vehicles yield no emissions and therefore cause no environmental or ecological impact.

Various environmental impact metrics exist for vehicle use. Life cycle assessment (LCA) has been widely adopted. For example, Maclean and Lave (2000) analyze and compare various fuel-powertrain options for internal combustion engine automobiles (spark and compression ignited, direct injected, and indirect injected engines fueled by conventional and reformulated gasoline, reformulated diesel, compressed natural gas and alcohols) using the metrics of fuel/engine efficiency, energy use, pollutant discharges and greenhouse gas emissions. But concerns exist about LCA. For instance, Seager and Brown (2001) criticize the study of Maclean and Lave (2000) because conditions (e.g., gasoline price) may vary temporally and geographically, causing conclusions to change. Also, Owens (1997) raises accuracy concerns because LCA often excludes spatial, temporal, dose-response and threshold information, and suggests that LCA may have limited value in the areas of local and/or transient biophysical processes and issues involving biological parameters (such as biodiversity, habitat alteration and toxicity). Finally, the environmental impact of a process is often quantified using emission masses, which is inadequate since it neglects the fact that certain emissions have greater impacts on the environment than others.

An alternative LCA approach is to weight emission quantities by their environmental impact potentials based using exergy, on the premise that exergy of unconstrained emissions has the potential to disturb the equilibrium of the environment and thus somewhat represents a potential environmental impact. This approach is used in this case study, which draws heavily on the work of Daniel and Rosen (2002) and examines emissions produced during the fuel life cycle for 13 fuel and vehicle combinations using exergy methods. The case study helps identify transportation fuels and technologies that are environmentally problematic and illustrates the benefits of the exergy approach in environmental-impact assessments.

26.2.1. Relevant Exergy Values and Their Determination

Chemical exergy is calculated as described in Section 26.1.3. Also, the reference environment used is that in Table 6.1, except that, as in Section 26.1.3, the reference-environment pressure is taken to be 1 bar instead of 1 atm. Table 26.4 lists specific chemical exergies of substances relevant to this section. The assumptions listed in that table regarding NO_x and SO_x compositions are based Wang (1999a) and Heywood (1988).

26.2.2. Description of Fuels and Vehicles

Thirteen fuel and vehicle combinations are considered, as shown in Table 26.5, where one or more fuel types is shown for each vehicle type. The fuels considered are commercially available, while the vehicles are either commercially available or likely to enter the market in the near future. Several points are made regarding the fuel-vehicle combinations:

- Spark-ignition (SI), direct injection engines use highly-stratified fuel delivery injected directly into the cylinder to burn the fuel more efficiently.
- Compression-ignition, direct injection engines are more fuel efficient than comparable conventional SI engines. These engines (and fuels) usually produce higher levels of particulate matter than SI engines.
- Flexible-fuel vehicles can run on gasoline or a blend of gasoline and methanol/ethanol. Flexible-fuel vehicles operating on up to 85% ethanol/methanol with gasoline are considered. Bi-fuel vehicles can operate on either conventional gasoline or an alternative fuel, taken here to be compressed natural gas (CNG). This vehicle type is suited to regions where alternative fuel depots are uncommon. Dedicated alternative fuel vehicles can only use one fuel type, but the engine and emission systems can be more finely tuned to the alternative fuel, permitting fewer vehicle operation emissions for such vehicles than flexible fuel or bi-fuel vehicles.
- Hybrid electric vehicles use both an on-board battery and electric motor and an internal combustion engine. The batteries are charged as the vehicle slows using the electric motor(s) as generators. Grid-connected hybrid vehicles can also have their batteries recharged from the electrical grid, unlike grid-independent hybrid vehicles.

The selected feedstock for each fuel is indicated where appropriate in Table 26.6, since feedstocks can differ for some fuel types. Passenger cars, rather than light- and heavy-duty trucks, are considered.

Table 26.4. Specific chemical exergies of selected substances

Component	Specific chemical exergy (kJ/kmol)[a]
CO	275,100
CH_4	831,650
N_2O	106,880
CO_2	19,870
NO_x (assumed to be nitrogen monoxide (NO)	55,600
SO_x (assumed to be sulfur dioxide (SO_2)	313,400

[a] Determined with JANAF Thermochemical Tables (Chase Jr., 1998).

Table 26.5. Fuel-vehicle combinations considered

Vehicle type	Fuel type
Conventional spark ignition engine	Conventional gasoline
	Federal reformulated gasoline
	California reformulated gasoline
Conventional CIDI engine	Conventional diesel
Bi-fuel	Compressed natural gas (CNG)
Dedicated alternative fuel	Compressed natural gas
	Liquefied petroleum gas
	Electricity
Flexible fuel	Methanol (M85 blend)
	Ethanol (E85 blend)
SIDI hybrid electric: Grid-connected	California Phase 2 reformulated gasoline
SIDI hybrid electric: Grid-independent	Federal Phase 2 reformulated gasoline
Grid-independent CIDI hybrid electric	Conventional diesel

Table 26.6. Fuels considered and their corresponding feedstock(s)

Fuel	Feedstock	Feedstock composition (%)
Conventional/reformulated gasoline*	Petroleum	100
Conventional diesel	Petroleum	100
Compressed/liquefied natural gas	Natural gas	100
Liquefied petroleum gas	Natural gas	60
	Petroleum	40
Ethanol	Dry-milling corn	33
	Wet-milling corn	67
Methanol	Natural gas	100
Electricity**	Coal	53.8
	Uranium	18.0
	Natural gas	14.9
	Hydropower, solar energy and wind	12.3
	Petroleum (residual oil)	1

* 2.0% MTBE volumetric content assumed for conventional gasoline (Stork and Singh, 1995). 2.7% oxygen by weight assumed for Federal Phase 2 reformulated gasoline, and 2.1% for California reformulated gasoline (Wang, 1999a). MTBE is selected to meet these requirements.

** Based on average U.S. electricity generation mix (Argonne National Laboratory, 1998).

26.2.3. Emissions Considered

Emissions of CH_4, CO, CO_2, NO_x, N_2O and SO_x are considered. Other hydrocarbons, particulate matter, and volatile organic compounds are excluded for simplicity. That is not to imply that these emissions, for which data are available for fuel life cycles (Wang, 1999b), are not important. Particulate matter affects human health and is responsible for soot and smoke produced during fossil fuel combustion and other processes. Volatile organic compounds are generally composed of many different chemicals, the composition being process dependent. Hydrocarbons can lead to smog and ozone production.

Most of the emissions are associated with combustion, but emissions from non-combustion processes in the fuel cycle are also considered. These include: emissions from fuel spillage during feedstock transport and storage; fuel transport, storage and distribution; emissions from flaring and venting of gas in oil fields and from petroleum refining; methane emissions from natural gas pipeline transmission and processing; methane emissions from coal mining and processing during coal-based electricity generation; carbon dioxide emissions when natural gas is converted to methanol; and nitrogen oxides and nitrous oxide emissions from the nitrification/denitrification and washing out of nitrogen fertilizers. The latter emission is relevant during feedstock production of corn for the ethanol in the E85 fuel.

26.2.4. Data

Normalized data are used to permit reasonable and consistent comparisons. The normalized data are obtained using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model (Wang, 1999a, 1999b), developed by the Center for Transportation Research at Argonne National Laboratory. For a given fuel/vehicle combination, GREET calculates the fuel life cycle consumption of energy (from all sources) and fossil fuels, and the emissions of CO_2, CH_4, N_2O, CO, NO_x, SO_x, volatile organic compounds and particulate matter with a diameter of 10 micrometers or less. GREET has been found to provide results that compare favorably to measured emission data from non-affiliated sources, and is used by various industries (including automotive), e.g., GREET emissions data were used to compare the fuel life cycle emissions of trucks utilizing CIDI engines fueled with LPG, CNG and diesel (Ouellette, 2001). A modified version of GREET is used to calculate the chemical exergies of emissions in addition to the masses of emissions produced during the fuel life cycle.

26.2.5. Methodology

The fuel life cycle is taken to be composed of three stages:

- *Feedstock*: The feedstock stage includes processes used during feedstock recovery through to feedstock delivery and fuel production, and includes recovery, transportation and storage of the energy feedstocks.

- *Fuel*: The fuel stage encompasses fuel-production activities between the delivery of the feedstock to the fuel production plant and the delivery of the fuel to the refueling station, and includes fuel production, transport, storage and distribution.
- *Vehicle*: The vehicle stage begins after the fuel stage, and includes fuel delivery to the refueling station through to fuel use to provide a service during vehicle operation.

The fuel life cycles are chosen to approximate emissions from passenger cars undergoing the U.S. Federal Test Procedure (Wang, 1999a). The baseline conventional gas vehicle is taken to be a passenger car with a fuel economy of 10.5 liters per 100 kilometers. Estimated fuel economies of other vehicle types considered are presented in Table 26.7.

Estimated vehicle stage emissions may not be indicative of actual emissions, as road type, driving behavior and engine temperature affect tail-pipe emissions and fuel economy (De Vlieger, 1997). Since reduced fuel economy can increase upstream emissions in the fuel life cycle, as more fuel is then produced for the vehicle to travel the same distance, data presented herein likely underestimate actual fuel life cycle emissions. However, using vehicle emissions estimated with the U.S. Federal Test Procedure facilitates consistent comparisons.

The methodology employed has several limitations, the main ones being exclusion of volatile organic compound, hydrocarbon and particulate emissions, and use of three phases of the life cycle, rather than a full cradle-to-grave vehicle life cycle. A full life cycle analysis would better estimate the total impact on the environment for a given fuel-vehicle combination, e.g., chemical components of the batteries (lithium, nickel-cadmium, etc.) in dedicated electric and hybrid electric vehicles are highly out of equilibrium with the environment, so their disposal is important at the end of the vehicle life. A vehicle life cycle analysis combined with the fuel life cycle would likely indicate electric and hybrid vehicles to be less environmentally benign than a fuel life cycle analysis alone would indicate.

Table 26.7. Estimated fuel economies for selected vehicles*

Vehicle/fuel type	Fuel economy (liters per 100 kilometers)
Baseline conventional gasoline vehicle: CG	10.5
Conventional gasoline vehicle: FRFG2	10.5
Conventional gasoline vehicle: CRFG2	10.5
CIDI vehicle: conventional diesel	7.8
Bi-fuel CNGV: CNG	11.7
Dedicated CNGV	11.3
Dedicated LPGV	10.5
M85 flexible fuel vehicle	10.0
E85 flexible fuel vehicle	10.0
Electric vehicle	3.5
Grid-connected SIDI HEV: grid operation	3.5
Grid-connected SIDI HEV: CRFG2	5.8
Grid-independent SIDI HEV: FRFG2	5.5
Grid-independent CIDI HEV: conventional diesel	5.2

* Adapted from Wang (1999a).

The methodology acknowledges that emissions for some fuels are strongly dependent on the input energy and feedstocks, as explained in the following two subsections.

Feedstock and CO_2 Sequestration in the E85 Fuel Life Cycle

One alternative fuel is E85 (85% ethanol and 15% conventional gasoline by volume). The ethanol component can be formulated from several biological feedstocks. Corn is considered as the feedstock here since it is commonly used for ethanol production. Woody and herbaceous biomass can also be used, but are less common. Lynd et al. (1999) suggests that biomass feedstocks are available on a large scale and are cost-competitive with petroleum.

During plant respiratory processes during corn growth, CO_2 is removed from air. The CO_2 sequestered during the feedstock stage is applied as a credit to the other stages of the fuel life cycle for ethanol, to facilitate the calculations of the chemical exergy of CO_2 emissions. For the E85 FFV fuel life cycle, 248 g of CO_2 is sequestered in the feedstock stage (per vehicle mile traveled), and a corresponding credit is applied to the CO_2 emissions as follows:

- Fuel stage (before/after CO_2 emissions after credit applied): 183 g/0 g
- Vehicle stage (before/after CO_2 emissions after credit applied): 370 g/305 g
- Total fuel life cycle (before/after CO_2 emissions after credit applied): 553 g/305 g

Although it is difficult to specify exactly where sequestered CO_2 should be applied, the total CO_2 released during the fuel life cycle is not affected by sequestration approximations. Wang et al. (1997, 1999) quantitatively discuss CO_2 sequestration in their overview on the biomass to ethanol process. Some suggest CO_2 credit should be applied with caution (Berthiaume et al., 2001) and that analyses also should be done without CO_2 credits.

Electricity-generation Mix

For dedicated electric vehicles and grid-connected HEVs, the mix of energy resources used for electricity generation can greatly affect emissions during the fuel life cycle. Table 26.6 lists the United States average electricity-generation mix, which is used here and in GREET to estimate emissions data. In actuality, grid-connected HEVs and electric vehicles do not use the average electricity generation mix, since electricity generation mixes vary regionally, as do seasonal climatic and peak vs. off-peak electricity demand parameters (Argonne National Laboratory, 1998). Thus emissions vary when region-specific study data are used, as was done in a study for the Lower Fraser Valley (Lewinson, 2001). For the grid-connected hybrid vehicle, 30% of vehicle miles traveled are assumed to be via grid electricity, with on-board devices supplying the power for the remaining 70% of VMT (Wang, 1999a).

26.2.6. Life Cycle Emissions and Their Exergies

The emissions results, normalized to a per unit vehicle mile traveled (VMT) basis, are presented for each fuel/vehicle case in Figures 26.2 and 26.3. The results are shown for the overall fuel life cycle and broken down into the three stages comprising it, and are presented on mass and chemical exergy bases.

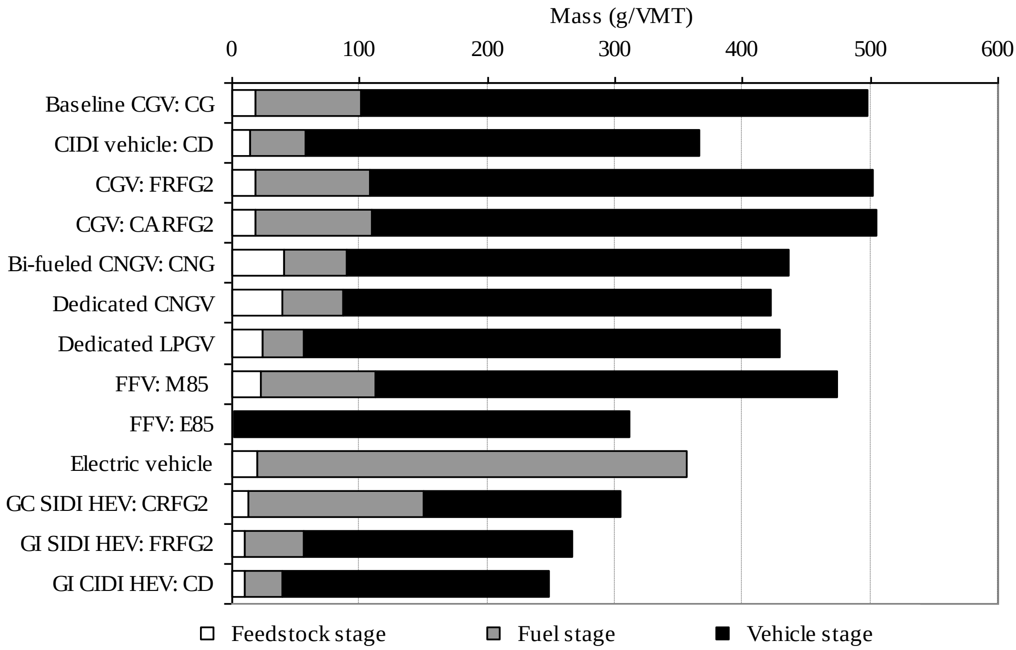

Figure 26.2. Total mass of emissions produced during the fuel life cycle per vehicle mile traveled. The vehicle type and fuel are shown where appropriate.

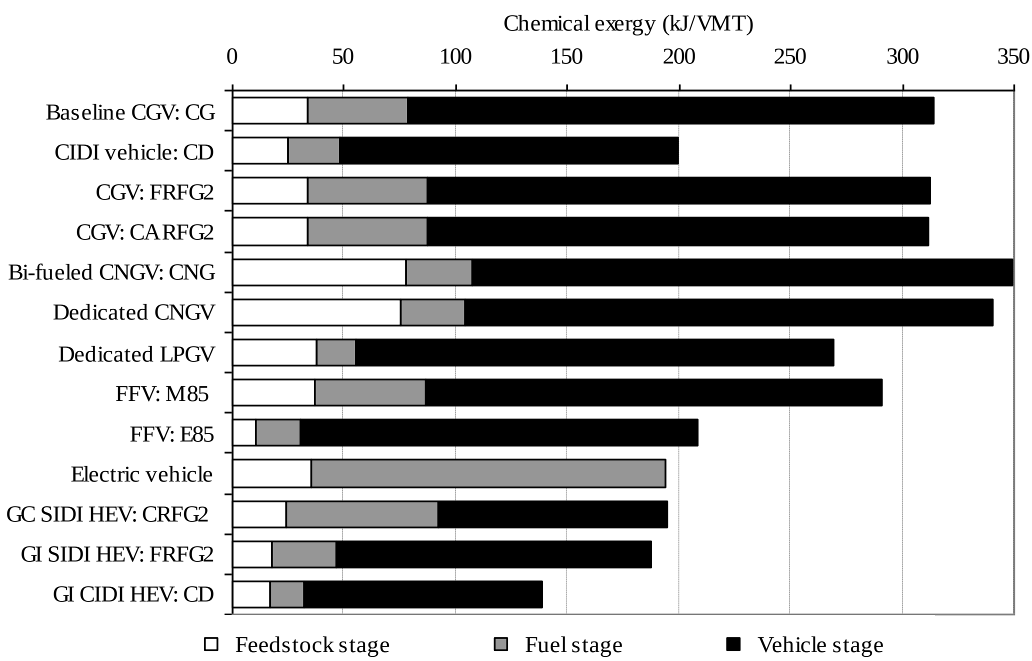

Figure 26.3. Total chemical exergy of emissions produced during the fuel life cycle per vehicle mile traveled. The vehicle type and fuel are shown where appropriate.

Overall Fuel Life Cycle

We first consider mass emissions. The total emissions mass for the overall fuel life cycle (i.e., feedstock, fuel and vehicle stages) is presented in Figure 26.2, with contributions of each stage. Conventional vehicles fueled with reformulated gasolines (U.S. Federal and California) yield more emissions than the life cycle for the same vehicle type fueled with conventional gasoline. This result is attributable to the fuel stage, where more resources are expended on reformulated gasoline to reduce its combustion emissions. Vehicle-stage emissions for reformulated gasolines are slightly lower than those for conventional gasoline. The data in Figure 26.2 suggest that the fuel life cycle for the grid-independent diesel hybrid vehicle is the most environmentally benign. But, this analysis omits particulate matter, and diesel vehicles generally exhaust more particulate matter than comparable spark ignition vehicles.

We now consider chemical exergy emissions. The total chemical exergies of emissions for the fuel life cycle, and the contributions of the feedstock, fuel and vehicle stages, are shown in Figure 26.3. The fuel life cycle for the electric vehicle is more environmentally benign than that for the E85 FFV or the grid-connected hybrid vehicle, on the basis of exergy. This result contrasts with the mass analysis of Figure 26.2, where the fuel life cycle for the grid-independent diesel hybrid vehicle appears to be the most environmentally benign. From an exergy perspective, the CNG vehicles exhibit the potential to cause greater environmental impact, mainly due to the CH_4 emissions produced during the fuel life cycle.

It is helpful to expand on the latter point since CH_4 is emitted during the transmission and distribution of natural gas (National Risk Management Laboratory, 1996; EIA, 1997). For the feedstock and fuel stages, 27% of methane emissions occur during natural gas production, 12% during processing, 37% during transportation and storage, and 25% during distribution (National Risk Management Laboratory, 1996). However, Harrison and Cowgill (1996) suggest that an increase in demand for natural gas would decrease CH_4 emissions as a percentage of natural gas production. Additionally, it is assumed the vehicle stage for natural gas-powered vehicles produces ten times the CH_4 emissions compared to the baseline CG vehicle, but advancements in vehicle technologies will likely reduce these emissions.

Breakdown by Emission Type

During the feedstock stage, CO_2 is the dominant pollutant on a mass basis per VMT, except in the case of E85 feedstock production, where CO_2 is sequestered. Nitrification/denitrification and washing out of the fertilizer applied to the cornfield accounts for the relatively high N_2O and NO_x emissions produced during the E85 fuel cycle. The feedstock stage for compressed natural gas produces more CO_2 than any of the other fuel-vehicle combinations presented, as well as the most methane gas.

The breakdown of pollutants during the feedstock stage differs when based on emission chemical exergy. Although the mass of CH_4 emissions is small, it is the most predominant emission from a chemical exergy perspective. This result is due to methane's high specific chemical exergy and is especially significant for the CNG feedstock stage. From the chemical exergy view, the feedstock stage for E85 is the most environmentally benign (as it also is based on mass), but the advantage is less based on chemical exergy due to the contribution of CO, NO_x and CH_4, which have much higher specific chemical exergies than CO_2. In all cases, CO contributes more to emissions based on chemical exergy than on mass.

During the fuel stage, CO_2 is the dominant pollutant on mass and chemical exergy bases, except for the E85 FFV case, which has no CO_2 emissions because of its CO_2 sequestration credit. The E85 FFV has little small emissions (mainly NO_x, CH_4, SO_x and CO), but the chemical exergy contributions of these emissions are more significant. Higher chemical exergies of emissions are observed for the fuel stage for the E85 FFV than for both the dedicated LPG vehicle and the grid-independent diesel hybrid vehicles. The fuel stage for the dedicated electric vehicle produces the highest emissions, but the values are dependent on the assumed electricity-generation mix (see Table 26.6). Because of its dependence on the electrical grid, the fuel stage for the grid-connected hybrid vehicle produces more emissions on mass and chemical exergy bases than the two grid-independent hybrid vehicles.

During the vehicle stage, the dedicated electric vehicle produces no emissions (recalling we are not considering particulate emissions, e.g., from brake and tire wear). As in the feedstock and fuel stages, CO_2 makes up most of the masses of emissions per VMT. Carbon monoxide also is notable, but to a smaller extent. On a mass basis, the diesel vehicles produce less CO and CH_4, but more NO_x and SO_x (and particulate matter), than the SI engine vehicles.

While CO only accounts for little of the emissions masses for the vehicle stage, its contribution to the total chemical exergies of emissions is much more notable. Also, CH_4 emissions, especially for the CNG vehicles, are more significant on a chemical exergy rather than a mass basis. Due to the large contribution of CH_4 to the chemical exergies of emissions, CNG vehicles may have a greater potential for environmental impact than all other fuel-vehicle combinations considered for the vehicle stage. This result contrasts greatly with the mass-based data, where the CNG vehicles appear to be the most environmentally benign spark ignition vehicles during this stage (with the possible exception of the flexible fuel E85 vehicle after the feedstock CO_2 sequestration credit). For the diesel vehicles, the emission contributions from NO_x and SO_x are more notable based on chemical exergy than mass.

26.2.7. Environmental and Ecological Interpretation

The characteristics of exergy, especially chemical exergy, suggest it may be usable as an indicator, or part of an indicator, of potential for environmental impact. Flows with greater chemical exergy are likely to have higher potential for environmental impact because they are further out of equilibrium with the environment than flows with lower exergy. Of the 13 fuel life cycles considered here, the fuel life cycle emissions for the two CNG vehicles are, from the chemical exergy perspective, the furthest out of equilibrium with the environment. Also, the grid-independent CIDI hybrid vehicle has the lowest emission chemical exergies, and thus may be the most environmentally benign (omitting volatile organic compounds, particulate matter and hydrocarbon emissions).

26.3. Exergy-Based Life Cycle Analysis of Vehicles and Fuels

Extending the case studies in the two previous sections, an exergetic life cycle assessment is presented of four vehicle types, based on prior research (Granovskii et al., 2006b, 2007).

Table 26.8. Principal steps in producing and using various transportation fuels

Step	Fuel and vehicle			
	ICE vehicle using crude oil-derived gasoline	Fuel cell vehicle using natural gas-derived hydrogen	Fuel cell vehicle using solar-derived hydrogen	Fuel cell vehicle using wind-derived hydrogen
Primary energy extraction/ conversion	Crude oil extraction	Natural gas extraction	Photovoltaic electricity generation	Wind turbine electricity generation
Transport	Crude oil pipeline transport	Natural gas pipeline transport	Electricity transmission	Electricity transmission
Conversion to final fuel	Refining to gasoline	Steam reforming to hydrogen	Hydrogen production by electrically driven water electrolysis at fueling station	Hydrogen production by electrically driven water electrolysis at fueling station
Fuel compression	-	Hydrogen compression	Hydrogen compression	Hydrogen compression
Fuel distribution	Gasoline distribution	Compressed hydrogen distribution	Compressed hydrogen distribution	Compressed hydrogen distribution
Fuel use	Gasoline use in ICE vehicle	Hydrogen use in fuel cell vehicle	Hydrogen use in fuel cell vehicle	Hydrogen use in fuel cell vehicle
Emission treatment	Exhaust treatment and emission	Exhaust (water) emission	Exhaust (water) emission	Exhaust (water) emission

26.3.1. Vehicles and Fuels Considered

The vehicle types considered, and their fuels, are as follows:

- Two vehicles using fossil fuels:
  - Internal combustion engine (ICE) vehicles operating on gasoline from crude oil.
  - Fuel cell vehicles operating on hydrogen fuel derived from natural gas.
- Two vehicles using renewable energy:
  - Fuel cell vehicles operating on hydrogen derived from solar energy.
  - Fuel cell vehicles operating on hydrogen derived from wind energy.

26.3.2. Life Cycle Steps

The main steps in the life cycles for these vehicles and their fuels that are considered in the analysis are shown in Table 26.8. Details on the main steps follow:

Natural Gas and Crude Oil Transport

The exergy consumption and environmental impact are evaluated for transporting natural gas and crude oil by pipeline. The exergy values embodied in materials (e.g., pipeline materials) and devices (e.g., compressors and pumps) are evaluated assuming the only fossil fuel employed in their production is natural gas. The mechanical work or electricity required for pipeline transport is assumed produced by a gas turbine.

Natural Gas Reforming

The direct exergy losses in natural gas reforming, where natural gas is the only source of exergy input, are considered (Rosen, 1996a, 1996b), as are the indirect exergy uses in natural gas reforming, including material requirements. The indirect exergy consumption is much smaller than the direct exergy consumption.

Crude Oil Distillation

The direct and indirect exergy losses in crude oil refining are considered. The indirect exergy consumption in this step is negligible compared to the direct exergy consumption.

Hydrogen Production from Wind

Direct and indirect exergy uses are considered. The system considered here for producing hydrogen from wind energy involves a wind turbine to generate electricity by first converting wind to mechanical work and then transforming it to electricity in an alternator, followed by an electrically driven water electrolyzer that produces hydrogen.

Hydrogen Production from Solar Energy

Direct and indirect exergy uses are evaluated for the process of hydrogen production using solar energy. This process involves a solar photovoltaic system to generate electricity, followed by an electrically driven water electrolyzer that produces hydrogen.

Hydrogen Compression

Hydrogen is often compressed to facilitate its storage and utilization. A natural gas-fired gas turbine drives the compressor. The direct and indirect exergy consumptions are evaluated.

Hydrogen and Gasoline Distribution

In the pre-operation phase, hydrogen distribution is local and accounted for in hydrogen production. Energy distribution over longer distances is accommodated via electricity distribution for the wind and solar energy cases.

Table 26.9. Life cycle assessment of the exergy efficiency of fossil fuel and material resource utilization to produce hydrogen and gasoline

Vehicle	Vehicle fuel	Fuel source	Fuel pressure (atm)	Overall life cycle exergy efficiency (%)
Fuel cell	Hydrogen	Natural gas	350	64
Fuel cell	Hydrogen	Wind energy	350	169
Fuel cell	Hydrogen	Solar energy	350	62
Internal combustion engine	Gasoline	Crude oil	1	85

In the operation phase, the distribution of compressed hydrogen after its production via natural gas reforming is similar to that for liquid gasoline. Compressed hydrogen typically has a lower volumetric energy capacity than gasoline and requires a larger capacity tank.

26.3.3. Life Cycle Exergy Efficiencies

Table 26.9 summarizes the overall ExLCA results. The life cycle exergy efficiency of fossil fuel and material resource use is defined for hydrogen production as the ratio of the hydrogen exergy to the overall life-cycle fossil fuel and material exergy consumption to produce the hydrogen, and for gasoline production as the ratio of the gasoline exergy to the overall life-cycle fossil fuel and material exergy consumption to produce the gasoline. The life cycle assessment of the exergy efficiency of fossil fuel and mineral resource utilization to produce compressed hydrogen from wind energy (169%) implies that the consumed fossil fuel exergy (embodied in materials, equipment, etc.) is 1.69 times less than the exergy of the hydrogen produced. The life cycle efficiency is greater than 100% because the exergy of wind is considered "free" and therefore not included in determining the efficiency. Note that the indirect exergy consumption rate for fossil fuel technologies is usually very small compared to the direct exergy consumption rate.

26.3.4. Environmental Implications

The exergetic life cycle assessment is extended to greenhouse gas and other air pollution emissions. The work can be viewed as considering substituting renewable wind and solar energy for fossil fuels to produce electricity and hydrogen. Emissions are determined during all process steps, including crude oil and natural gas pipeline transportation, crude oil distillation and natural gas reforming, wind and solar electricity generation, hydrogen production through water electrolysis, and gasoline and hydrogen distribution and utilization.

Some key environmental implications follow:

- Producing hydrogen via electrolysis using electricity from wind and solar energy, and use in a fuel cell vehicle, exhibits the lowest GHG and air pollution emissions.
- Substituting gasoline with "renewable" hydrogen leads to reductions in greenhouse gas emissions of up to 23 times for hydrogen from wind and eight times for hydrogen from solar energy, and air pollution emissions of up to 76 times for hydrogen from wind and 32 times for hydrogen from solar energy.
- Substituting gasoline with hydrogen from natural gas, on the other hand, leads to reductions in greenhouse gas and air pollution emissions of up to only five times.

26.4. Closing Remarks

The three case studies for automotive operations demonstrate, for conventional and advanced vehicle technologies as well as conventional and alternative fuels, illustrate the use of exergy as a kind of measure of the environment impact potential and the need to consider the full life cycle for a comprehensive assessment of environmental and ecological impacts. The first case study shows that the exergy of the operating emissions from methanol-fueled spark ignition engines are high (indicating greater environmental impact potential), whereas lower exergy emissions exist for a hydrogen/air fuel cell (suggesting a system better synchronized with the environment). The case study of the emissions for 13 fuel life cycles for automobiles illustrates that the chemical exergy of compressed natural gas use in vehicles produces emissions furthest from equilibrium with the natural environment, while diesel use in grid-independent hybrid electric vehicles exhibits the lowest emission chemical exergy, suggesting a lower degree of potential environmental impact. The case study involving exergetic life cycle assessments of four vehicle technologies extends the first two case studies to substituting renewable energy like wind and solar energy for fossil fuels and contrasts internal combustion engines with hydrogen fuel cells. The case studies demonstrate that exergy-based methodologies can help efforts to determine environmentally benign fuels and vehicle technologies and address transport-related environmental and ecological concerns.

Chapter 27

EXERGY-GUIDED ENVIRONMENTAL MANAGEMENT FOR COUNTRIES, REGIONS AND SECTORS

OVERVIEW

Environmental and ecological impacts, considering energy and exergy efficiencies and inefficiencies, are examined for two case studies: a region (Ontario) and a country (United States). The exergy analyses indicate less efficient resource utilization in Ontario and the U.S. than energy analyses. Energy analyses of energy utilization in the U.S. or Ontario do not provide clear pictures of how well resources are utilized and where emissions and other losses are likely to cause impacts. Exergy assessments help provide this information, and can indicate to industry and government where emphasis should be placed to improve exergy use associated with our main energy sources and to mitigate environmental and ecological impacts. Generalizations of the results are discussed.

The methodology for exergy-based environmental assessments of countries, regions and sectors, described in Section 10.9, is applied to two case studies: the United States and Ontario, Canada's most populous province. The case studies are based on previous analyses but are relevant today, and implications can be inferred from them for the present and future.

27.1. CASES CONSIDERED

In the first case study, the author uses the methodology described earlier to the province of Ontario, Canada and its sectors. Such a regional analysis is important not just for Ontario, but also for Canada, since Ontario accounts for over 30% of national energy use. Efforts to improve the efficiency with which energy resources are utilized in Canada to ensure they are used in the most appropriate manner and to control environmental emissions require careful attention to a province as significant as Ontario. This case study draws extensively on previous energy and exergy analyses of Ontario's energy sectors (Rosen, 1993).

In the second case study, the United States is considered. Data are drawn from earlier energy and exergy analyses of the U.S. (Reistad, 1975, 1980; Reistad and Gaggioli, 1980).

27.2. DATA AND ANALYSIS

27.2.1. Ontario, Canada

Actual and perceived inefficiencies evaluated previously by Rosen (1993) and Lemieux and Rosen (1989) are used. These inefficiencies are determined from the sector and total waste quantities given for Ontario in Figure 27.1 for energy and Figure 27.2 for exergy. Energy flow data are obtained from various sources, e.g., Supply and Services Canada (1988).

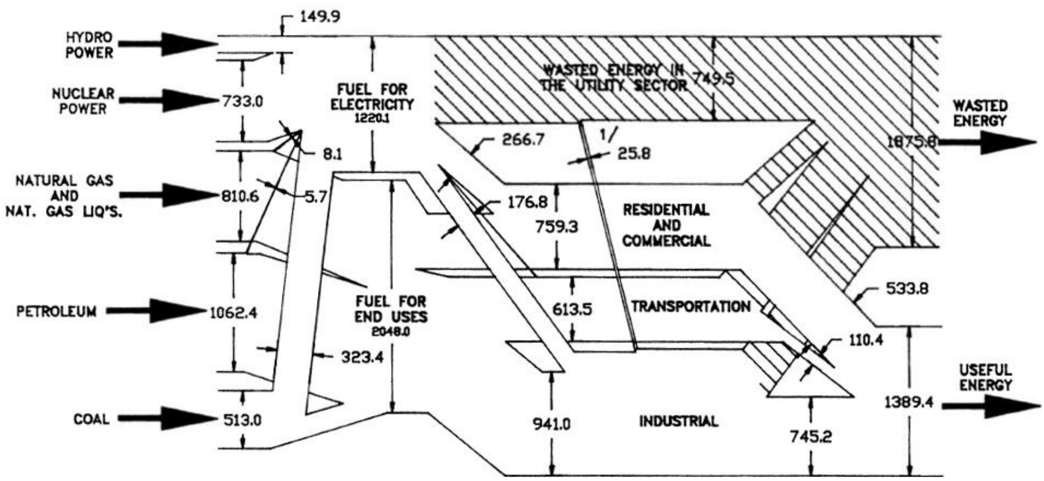

Figure 27.1. Energy flow diagram for Ontario (in PJ or 10^{15} J) for 1987. The hatched region denotes losses and the note "1/" indicates steam extracted from the utility sector. Hydraulic energy is shown in kinetic energy equivalent.

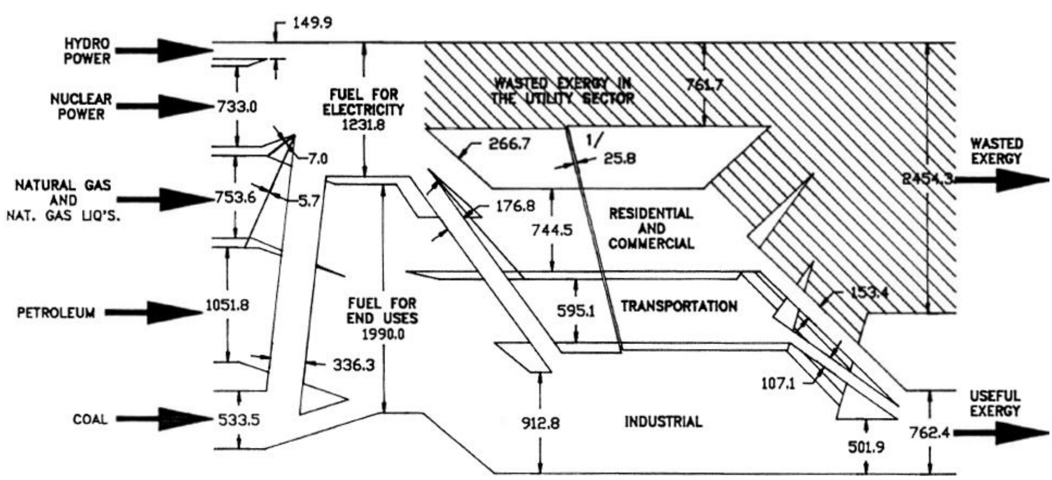

Figure 27.2. Exergy flow diagram for Ontario (in PJ or 10^{15} J) for 1987. The hatched region denotes losses (external exergy emissions and internal exergy destructions) and the note "1/" indicates steam extracted from the utility sector. Hydraulic exergy is shown in kinetic exergy equivalent.

It is observed that 43% of Ontario's total energy use is converted to useful energy for end uses, while only 24% of Ontario's exergy use is converted to useful exergy. The most efficient sector based on energy is the residential sector (74%), followed by the commercial (66%), industrial (65%), utility (39%) and transportation (18%) sectors. The most efficient sector based on exergy is the industrial sector (45%), followed by the utility (39%), commercial (27%), transportation (18%) and residential (16%) sectors.

The exergy efficiencies are low in the residential and commercial sectors due to their poor utilization of the quality (or work potential) of the input energy. In these sectors, energy is primarily used to produce heat. With the production of heat from a fossil fuel or electrical energy source, there is a loss in the quality of energy that is reflected only with exergy. The lower the temperature of the heat produced, the lower is the exergy efficiency. A wide variation between energy and exergy efficiencies is seen in the residential, commercial and industrial sectors, attributable mainly to the extent to which they use heating and cooling.

Note that the exergy analysis of Ontario compares well with similar analyses for Canada (Rosen, 1992). For instance, the overall energy and exergy efficiencies respectively are 43% and 24% for Ontario and 51% and 24% for Canada (see Tables 27.1 and 27.2). Furthermore, sector efficiency trends for Canada are similar to those for Ontario in all but the utility sector. For example, the industrial, transportation and residential-commercial sectors in Ontario have exergy efficiencies of 45%, 19%, and 21% respectively, while in Canada these sectors exhibit exergy efficiencies of 42%, 19%, and 14% respectively. The utility sector in Ontario does not follow the trend of the national average, having an efficiency of 39% compared to Canada's 53%, mainly because of the extent nuclear electricity generation in Ontario. That is, Canada generates a larger percentage of its electricity in highly efficient hydraulic utilities than Ontario, which produces about half of its electricity in less efficient nuclear utilities.

Table 27.1. Energy efficiencies (in %) for selected regions, broken down by sector*

Sector	Ontario	Canada	Turkey	Saudi Arabia
Residential-commercial	70	72	69	81
Transportation	18	19	22	22
Industrial	65	73	68	63
Utility	39	53	45	32
Overall	43	51	42	60

* Source: Dincer and Rosen (2007). Data are from 1993 for Turkey and Saudi Arabia, 1986 for Canada, and 1987 for Ontario.

Table 27.2. Exergy efficiencies (in %) for selected regions, broken down by sector*

Sector	Ontario	Canada	Turkey	Saudi Arabia
Residential-commercial	21	14	12	10
Transportation	18	19	22	22
Industrial	45	42	42	40
Utility	39	53	45	32
Overall	24	24	26	39

* Source: Same as for Table 27.1.

Table 27.3. Breakdowns of actual and perceived sector inefficiencies for Ontario

Sector	Breakdown of overall inefficiency (%)	
	Perceived inefficiency portion attributable to sector	Actual inefficiency portion attributable to sector
Residential-commercial	12	24
Industrial	21	25
Transportation	27	20
Utility	40	31
Overall	100	100

27.2.2. United States

Reistad (1975, 1980) and Reistad and Gaggioli (1980) apply exergy analysis to energy utilization in the United States in order to calculate energy sector efficiencies and losses. The inefficiency breakdowns are calculated using Equations (10.6) through (10.9).

27.2.3. Reference Environment

The reference environment in Table 6.1 is used in the case studies, except that necessary modifications are made for some processes (e.g., using a reference-environment temperature that is representative of the mean annual or seasonal temperature of the region considered).

27.3. Results and Discussion

27.3.1. Ontario

A breakdown of inefficiencies for Ontario and each of its sectors is listed in Table 27.3, based on data in Figures 27.1 and 27.2. A sample calculation for the industrial sector follows for the breakdown of energy (perceived) and exergy (actual) inefficiencies. From Figure 13.2, the industrial sector is seen to contribute 613.5 PJ of waste exergy to the overall waste exergy (2454.3 PJ), so the actual inefficiency contribution of the industrial sector is as follows:

Industrial sector portion of overall actual inefficiency = 613.5/2454.3 = 0.25 (25%)

The perceived inefficiency breakdown is calculated similarly but using the waste energy values of Figure 27.1, which show that the industrial sector contributes 398.4 PJ of waste energy to the overall waste energy (1875.8 PJ). Therefore,

Industrial sector portion of overall perceived inefficiency = 398.4/1875.8 = 0.21 (21%)

A key trend of the inefficiency breakdown for Ontario is that actual inefficiencies are higher than perceived inefficiencies in the residential-commercial and industrial sectors, and lower than perceived inefficiencies in the transportation and utility sectors.

27.3.2. United States

Table 27.4 shows inefficiencies for the U.S. and each of its sectors, in the form of a breakdown of actual inefficiencies, as a percentage of total exergy loss in the sector, and the perceived inefficiencies, as a percentage of the total energy loss in the sector. The industrial sector consumes the most energy of any end use sector (Gaggioli, 1983) and has the most room for improvement on an exergy basis, even though it is perceived as being the most efficient sector on an energy basis. The utility sector has the smallest losses on an exergy basis while, based on energy, it is second to the transportation sector in losses.

27.3.2. Comparison

Several common trends are revealed by comparing the case study results in Tables 27.3 and 27.4. For Ontario and the U.S., actual inefficiencies in the residential, commercial and industrial sectors are higher than the perceived inefficiencies, while actual inefficiencies are lower for the transportation and utility sectors. Also, actual inefficiencies seem not to be well understood, while perceived inefficiencies are commonly viewed as significant. But, somewhat different behavior is observed for the industrial sectors, in that the industrial sector in Ontario has a perceived inefficiency of 21%, which is higher than anticipated based on perceived efficiencies, while the U.S. industrial sector has a perceived inefficiency of 32%. Two reasons why energy and exergy industrial-sector results for Ontario vary from those for the U.S. are size (Ontario is a province with a population of about 13 million while the U.S. is a country with a population over 300 million), and the industrial activities in each jurisdiction.

27.4. INTERPRETATION

The results for both cases provide important insights into the environmental and ecological impacts of the regions and their economic sectors, particularly since the results stipulate the following clearly:

- *How resources are utilized in the regions and their economic sectors*. This provides information on environmental and ecological harm via the need to extract natural resources to meet the needs of countries and regions, and their economic sectors.
- *Where losses occur and waste emissions are expected*. These represent possible potentials for environmental and ecological damage, due to the exergy associated with the unconstrained emissions.

Table 27.4. Breakdowns of actual and perceived sector inefficiencies for the U.S.

Sector	Breakdown of overall inefficiency (%)	
	Perceived inefficiency portion attributable to sector	Actual inefficiency portion attributable to sector
Residential-commercial	30	20
Industrial	32	15
Transportation	24	40
Utility	14	25
Overall	100	100

The results of the case studies, although based on past data, have implications for the present and future. Investigations of other regions, countries and sectors (see Section 27.5) using present and predicted future data support this observation. It is thus anticipated that several aspects of the trends indicated by the results of the case studies in terms of environmental and ecological impact are likely still valid today. In particular, losses are understood based on perceived rather than actual efficiencies, thereby potentially missing opportunities for large environmental improvements and efficiency gains by focusing on the sectors with the largest margins for efficiency improvement.

Given the breadth of countries and regions, it is important that an appreciation of exergy methods reaches the levels of policy makers and industry leaders, to help inform policies so that beneficial strategic steps can be taken to address environmental and ecological damage.

27.5. Extensions

The results for the case studies considered here can be extended by considering other countries and regions.

27.5.1. Analyses of Other Countries and Regions

Over the past few decades, exergy has been increasingly applied to regions and countries, as well as economic sectors. Some investigations have focused on general analysis methods, including a review of methods for evaluating the energy utilization efficiency of countries (Utlu and Hepbasli, 2007b). Also, exergy analyses have been compared for various societies, including Organization for Economic Co-operation and Development (OECD) countries and the world (Ertesvag, 2001). Exergy-based analyses have been performed for numerous countries, e.g., Canada (Rosen, 1992, 1993), the United States (Reistad, 1975; Ayres et al., 2003), Japan (Wall, 1990, 1991), China (Chen and Qi, 2007; Chen and Chen, 2006; Chen et al., 2006), the United Kingdom (Hammond and Stapleton, 2001; Gasparatos et al., 2009; Warr et al., 2008), Finland (Wall, 1991), Sweden (Wall, 1986, 1987, 1991; 1997), Norway (Ertesvag and Mielnik, 2000; Ertesvag, 2005), the Netherlands (Ptasinski et al., 2006), Italy (Wall et al., 1994), the former U.S.S.R. (Stepanov, 1995), Turkey (Ozdogan and Arikol, 1995; Dincer and Rosen, 2007; Ileri and Gurer, 1998), Saudi Arabia (Dincer and Rosen, 2007) and Brazil (Schaeffer and Wirtshafter, 1992). On a broader scale, global exergy-based analyses have been carried out (Nakicenovic et al., 1996; Hermann, 2006), as have evaluations of the exergy consumption of the Earth (Chen, 2005; Rosen and Scott, 2003).

27.5.2. Focused Sectoral Analyses

Numerous studies have focused on particular sectors in isolation, rather than as part of a larger assessment:

- *Industrial*. Exergy was utilized to assess energy and materials processing in industry and to compare industries (Brodyanski et al., 1994). Assessments have been undertaken of exergy use in industrial processes using artificial intelligence (De Jong et al., 1996) and the effect of reference-state temperatures on exergy assessments of industrial sectors (Utlu and Hepbasli, 2008a). Wall (1988) has examined energy and exergy flows in industrial processes. The industrial sectors of several countries have been investigated using exergy, including Turkey (Utlu and Hepbasli, 2007c; Hepbasli and Ozalp, 2003) and South Africa (Oladiran and Meyer, 2007).
- *Agricultural*. Energy and exergy utilization in the agricultural sector of Saudi Arabia has been investigated (Dincer et al., 2005).
- *Residential and commercial*. Genetic algorithms for estimating exergy inputs and outputs have been reported (Ozturk et al., 2004), as have investigations of the effect of the reference state on efficiencies for the residential and commercial sectors (Utlu and Hepbasli, 2007a). Residential sectors have been investigated using exergy for several countries, including Jordan (Al-Ghandoor et al., 2008), Turkey (Utlu and Hepbasli, 2003, 2005, 2006b, 2008b), with the latter investigation including a thermoeconomic analysis, and Malaysia (Saidur et al., 2007a, 2007b), with the latter including an assessment of the commercial sector.
- *Utility*. Exergy assessments have been reported for the utility sectors of Turkey (Utlu and Hepbasli, 2007d) and Saudi Arabia (Dincer et al., 2004a).
- *Transportation*. Exergy assessments have been reported for the transportation sectors for Turkey (Utlu and Hepbasli, 2006a; Ediger and Camdali, 2007), Greece (Koroneos and Nanaki, 2008), Jordan (Jaber et al., 2008), China (Ji and Chen, 2006), Malaysia (Saidur et al., 2007c) and Italy (Federici et al., 2008).
- *Public and private*. Energy and exergy use in the public and private sector of Saudi Arabia has been assessed (Dincer et al., 2004b).

27.5.3. Extended Comparative Assessment

Overall and sectoral energy and exergy efficiencies are compared for three countries (Canada, Turkey, and Saudi Arabia) and one region (the Canadian province of Ontario) in Tables 27.1 and 27.2. Although based on data for different years, the comparison nonetheless illustrates similarities and differences in the energy and exergy utilization for different types of countries. In most cases, the residential sector is the most efficient on an energy basis and the least efficient on an exergy basis. Energy and exergy efficiencies are similar for the U.S., Canada and Ontario, suggesting common energy-use trends.

27.5.4. Extension to Resource Use of Planets and Their Constituencies

The methods described in this chapter can be applied to broader systems, such as planetary systems and their subsystems. This is illustrated in Chapter 15, where an exergy-based perspective is provided of resources and their use by Earth and its primary constituencies: the biosphere, people and civilization's energy system.

27.5.5. Trends

The main results of the many of the investigations described in this section are significant, in that they identify general trends:

- Exergy analysis indicates a less efficient picture of energy flow through a country's economy than does energy analysis. Correspondingly, losses are greater than perceived, suggesting a greater potential for environmental impact than thought.
- The residential-commercial sector exhibits the greatest variation of all sectors, depending on whether energy or exergy is considered. This is due to the extent to which high-grade energy sources are utilized for low-grade energy demands. Relatedly, the most significant efficiency differences between energy and exergy analyses are caused by thermal processes (heating and cooling).
- The analyses could yield important industrial and socioeconomic benefits. Specifically, using the results in this chapter rather than those from conventional energy balances, the author feels that the efficiency of national and regional energy utilization is more clearly illuminated, and more rational assessments are obtained of potential for environmental and ecological impact. Consequently, the results could provide important guidelines and insights, to both industries and governments.

27.6. Closing Remarks

The case studies of national and regional environmental and ecological impacts, considering energy and exergy efficiencies and inefficiencies, yield many insights. Exergy analyses indicate less efficient resource utilization in Ontario and the U.S. than energy analyses. Actual inefficiencies in the residential-commercial and industrial sectors are higher than perceived inefficiencies, while for the transportation and utility sectors actual inefficiencies are lower. An energy analysis of energy utilization in the U.S. or Ontario does not provide a clear picture of how well energy resources are utilized, and where environmental emissions and other losses are likely to cause impacts. Exergy assessments can help inform industry and government of where emphasis should be placed to improve the use of the exergy resources and to mitigate environmental and ecological impacts.

Chapter 28

CLOSURE AND FUTURE DIRECTIONS

OVERVIEW

Some closing thoughts are provided on the alternative approach to environmental and ecological management described in this book, and the manner in which it integrates exergy with ecology and environmental impact. The significant potential offered by this approach to improve environmental and ecological management is discussed, and speculations are provided on possible future directions.

Some final thoughts are provided on exergy-based approaches to environmental and ecological management and speculations on what the future may hold in this field. The intent is to inform thinking on where researchers, practitioners and society may go from here in our common quest for a cleaner planet.

28.1. CLOSURE

Useful relations exist between exergy and both ecology and the environment, which differ from relations between energy and either ecology or the environment, and which provide the basis for exergy-based ecological and environmental methods. Such methods are useful in analysis, comparison and improvement activities. The methods combine thermodynamics with ecological and environmental concepts and can be used to achieve advantageous designs, accounting for observations that environmental and ecological health are correlated in some ways with exergy. The relations further suggest that environmentally advantageous systems may be developed by balancing exergy-based environmental, ecological, technical and economic factors.

Such methods are wide ranging and include reducing industrial emissions via increased exergy efficiency, design for environment and exergy, cumulative exergy consumption, exergergetic life cycle analysis, exergy-based industrial ecology, exergy-based ecological footprint analysis, exergy-based emission tolerances, resource renewability, EXCEM analysis, extended exergy accounting, and others.

This book also highlights the merits of exergy analysis over the more conventional energy analysis, from a thermodynamic perspective and also from a combined thermodynamic and environmental and ecological perspective. For instance, it is shown that exergy, but not energy, can be viewed as a kind of measure of the potential for ecological and environmental impact. It is also shown that exergy-based ecological and environmental indicators are useful and have a wide range of potential applications.

The many applications and case studies presented illustrate how these insights can assist in integrating thermodynamics into ecological and environmental management, especially by exploiting the correlations between exergy and environmental and ecological parameters. It is repeatedly observed that exergy factors, or should factor, into environmental improvement and ecological management. For well understood processes and technologies, the environmental and ecological benefits of the exergy-based methods in this book may be insightful because, although such processes have gradually evolved and improved over time, this has often been done through trial and error and not very systematically. For new technologies, the application of exergy-based environmental and ecological methods may lead to even more significant design modifications and performance improvements, by providing a technically sound approach and avoiding the need to wait for gradual improvements through experience, an often time consuming path.

It is hoped that this chapter helps enhance awareness and appreciation of the merits of exergy-based environmental and ecological methods as well as, on a more general level, exergy methods. It is further hoped that such awareness and appreciation will foster many applications of these methods. The understanding and benefits provided by exergy-based environmental and ecological methods for people, society and industry are likely to prove important in many ways, making it advantageous for many to develop a good appreciation of the methods and their benefits.

28.2. FUTURE DIRECTIONS

Future trends and directions are generally difficult to predict, especially for a young field like exergy-based environmental and ecological management. Nonetheless, reasoned speculations can be provided on possible future directions by considering historical developments, the present situation and predictions of future trends by experts in many fields.

Here, some thoughts are provided on the development and application of exergy-based environmental and ecological methods and other techniques that evolve from the integration of exergy, ecology and environmental impact. These are based mainly on the author’s experience and perceptions, but are also informed by ideas and discussions of many other researchers and practitioners.

Trends and directions related to exergy and ecology and environmental impact, which may come to fruition in the future, can be separated into three main areas:

- *Methodology improvements*. Developments will almost certainly continue in the area of exergy, environmental and ecological integration, leading to advanced and more user-friendly methods and tools for exergy-based environmental and ecological management. Improvements will likely span from enhanced understanding at the fundamental level (e.g., further exploring linkages between exergy and ecology, biology, and the environment) through to application-oriented developments. As part of these improvements, exergy-based environmental and ecological assessments and management will likely be increasingly integrated with economics, either by enhancing existing tools or by developing new methods that focus on this integration. Exergy-based environmental and ecological methods will likely incorporate, or be incorporated into, strategies to promote sustainability as well as sustainable development. Furthermore, enhanced exergy-based optimization methods that incorporate environmental and ecological aspects will likely be developed, as will systems synthesis methods that use these methodology advances and incorporate approaches such as artificial intelligence and genetic algorithms. As a consequence of these advances, questions regarding the extent to which exergy is adequately related to environmental impact and ecology to form a useful tool will be addressed, helping the discipline to mature.

- *Increasing recognition*. Greater meaningful recognition will develop in industry and government of the potential benefits of exergy-based environmental and ecological methods. This growth in recognition will likely parallel an increasing appreciation and utilization of exergy efficiency improvement efforts. Education efforts may expand gradually to ensure relevant educational programs cover exergy-based environmental and ecological management and to instill a broader understanding and appreciation of this field in the public and the media.
- *Increasing application*. Exergy-based environmental and ecological methods will be increasingly used in initiatives for environmental and ecological management, as a complement to other approaches. Such applications will grow gradually while the methods develop and mature, and then will likely appear in increasing numbers, especially as experiences are attained and the benefits become repeatedly demonstrated. This increased utilization will likely occur across a diverse array of fields and throughout the world, in both developing and developed countries. Utilization of exergy-based environmental and ecological methods will likely appear most often in industry, with the intent of meeting regulatory requirements cost effectively, and in government, to help guide environmental and ecological policy development and planning. Exergy-based environmental and ecological methods will also likely be applied in efforts and strategies to promote sustainable development, given the significance of environment and ecology to sustainability. Those utilizing environmental and ecological methods will likely include environmental planners, designers, engineers, scientists, regulators, and economists, as well as other managers and practitioners.

A summary is presented in Figure 28.1 of the likely future trends and directions for the field integrating exergy, ecology and the environment as well as exergy-based environmental and ecological methods and management. The information in the figure is based on reasoned extrapolation and speculation, combined with an appreciation of relevant historical developments. Figure 28.1 illustrates how the process of improvement is cyclical and iterative, with one trend likely to feed into another. Note that similar future trends and directions are also likely for exergy analysis itself.

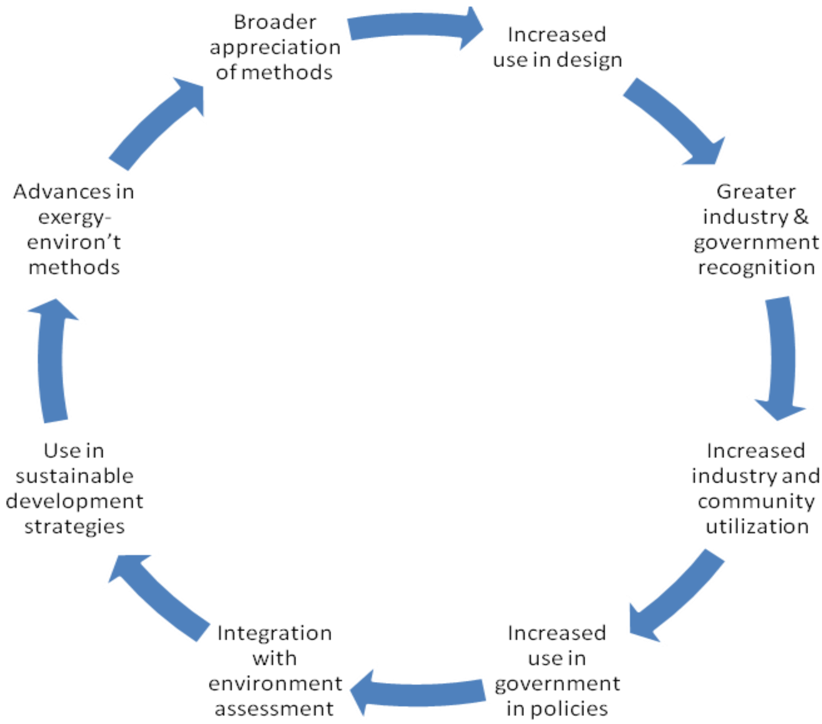

Figure 28.1. Possible future trends and directions related to exergy, environment and ecology as a discipline, as well as exergy-based environmental and ecological methods and management. The diagram illustrates how one trend is likely to feed into another, and how the process of environmental and ecological improvement and management is cyclical and iterative.

If these speculations regarding exergy-based environmental and ecological management come to pass, even in part, exciting and important benefits will likely accrue to humanity, industry and society through a cleaner environment and healthier ecosystems.

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