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Energy Systems Engineering

Evaluation and Implementation

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Third Edition

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Preface to the Third Edition

The goal of the third edition of *Energy Systems Engineering* remains the same as that of the first two: to provide both professional engineers and engineering students interested in energy systems with essential knowledge of major energy technologies, including how they work, how they are quantitatively evaluated, what they cost, and what is their benefit or impact on the natural environment. A second goal is to provide the reader with an overview of the context within which these systems are being implemented and updated today and into the future. Perhaps at no time in recent history has society faced such challenges in the energy field: the yearning to provide a better quality of life to all people, especially those in the more impoverished countries, coupled with the twin challenges of a changing energy resource base and the effects of climate change due to increased concentration of CO_2 in the atmosphere. Energy systems engineers from many disciplines, as well as nonengineers in related fields, will serve at the forefront of meeting these challenges.

It has now been 12 years since 2004 when we first began drafting chapters that would eventually become part of the first edition of the book, which was published in 2008. During that time, some energy trends have hardly changed at all. For example, the routine process of updating figures on CO_2 emissions and on the installation of renewable energy capacity highlights the challenge for the energy field around the world. Figure 4-3 gives world emissions of carbon from fossil fuel use, which in 2004 stood at 7.6 gigatonnes of carbon equivalent. That figure gives emissions for 2010 (the most recent year available from the U.S. Carbon Dioxide Information and Analysis Center) of 9.2 gigatonnes—an increase of 1.6 gigatonnes in the annual emissions rate in just six years. Not only does this increase represent the growing challenge of meeting energy needs without increasing atmospheric CO_2, but the increased emissions also symbolize newly added energy-consuming devices, ranging from large power plants to small individual private vehicles, for which populations will expect continued access to energy supplies in the years going forward.

On a more positive note, we have documented the many-fold increase in the installed capacity of solar and wind photovoltaic capacity around the world in Chaps. 10 and 13—by a factor of 27 for solar and a factor of 6 for wind from 2005 to 2013, measured in total installed gigawatts. Even the global CO_2 emissions data may be changing. Although they do not appear in Fig. 4-3, preliminary data from the International Energy

Agency show that 2014 was the first year in which the world economy grew compared to the previous year but with global CO_2 emissions remaining constant. These hopeful indicators suggest that individuals, businesses, and governments are beginning to embrace this challenge.

Turning from motivation to content, chapter topics have been chosen in the first part of the book to provide key background for the analysis of energy systems, and in the second part to give a representative view of the energy field across a broad spectrum of possible approaches to meeting energy needs. In Chaps. 1 to 3, we present tools for understanding energy systems, including a discussion of sustainable development, a systems approach to energy and energy policy, and economic tools for evaluating energy systems as investments. In Chaps. 4 and 5, we consider climate change and fossil fuel availability, two key factors that will shape the direction of energy systems in the twenty-first century. Chapters 6 through 14 present a range of technologies for generating energy for stationary applications, including fossil fuel combustion, carbon sequestration, nuclear energy, solar energy, wind energy, and biological energy. Chapters 15 and 16 turn to energy conversion for use in transportation systems, and Chap. 17 provides a brief overview of some emerging technologies not previously covered, as well as the conclusions for the book.

The contents of the book assume a standard undergraduate engineering background, or equivalent, in physics, chemistry, mathematics, and thermodynamics, as well as a basic introduction to statistics, fluid mechanics, and heat transfer. Each technology area is introduced from first principles, and no previous knowledge of the specific technologies is assumed.

This book originated in two courses taught at Cornell University, one in the School of Mechanical and Aerospace Engineering entitled "Future Energy Systems," and the other in the Department of Biological and Environmental Engineering entitled "Renewable Energy Systems." In addition, a third course, "Civil Infrastructure Systems," taught in the School of Civil and Environmental Engineering, influenced the writing of passages on sustainable development and systems engineering. Energy system concepts, example problems, and end-of-chapter exercises have been developed through introduction in the classroom. In both courses, we have focused on solar and wind energy systems, so we have also placed a special emphasis on these two fields in this book. Interest in solar and wind energy is growing rapidly at the present time, but information about these fields may not be as accessible to some engineers, so we aim to provide a useful service by giving them extensive treatment in Chaps. 9 through 13.

Presentation of technical content in the book adheres to several premises for energy systems engineering that are independent of the technologies themselves. The first is that *energy systems choices should be technology-neutral*. No energy system is perfect, and every system has a range of advantages and disadvantages. Therefore, to the extent possible, the choice of any system should be based on choosing criteria first and then finding a system, or mixture of systems, that best meets those criteria, rather than preordaining that one type of system or another be chosen. Fossil fuels have the major drawback of greenhouse gas emissions, and nuclear energy must contend with the management of high-level nuclear waste, so these factors may point to renewables as the preferred option. However, renewables in turn suffer from intermittency, diffuseness, and high initial capital cost.

Members of the general public see that our current energy system is imperfect, and sometimes respond by insisting that they be provided a perfect energy system. It is the

A second premise is that *there is value to a portfolio approach to energy options*. The value of the portfolio approach still holds, but the interpretation has changed since 2004, and this may represent one of the largest shifts as the book goes to a third edition. Several factors at this time point to renewable energy emerging as the eventual dominant energy source, rather than an energy system that is evenly shared among different resources. First, the rate of greenhouse gas emissions, and the extent to which the climate is changing rapidly, is greater than was anticipated a decade ago. This development puts great urgency on accelerated action to address climate change. Second, the other two primary energy sources—fossil with sequestration and nuclear—are not growing as rapidly as might have been anticipated, given the severity of the climate change problem. For sequestration, there has been only modest investment in capacity, although several projects continue to demonstrate proof of concept. For nuclear, the Fukushima accident and its aftermath dampen enthusiasm for the high capital cost of new plants in many countries. The third and final development is the rapid growth of renewable energy sources such as solar and wind, led by the growing manufacturing capacity of China and the low cost and improving reliability of the technology.

Nevertheless, there are educational reasons, separate from the desirability of one technology over another, to continue to include all three sources in this book, both in detail and keeping up-to-date with the latest developments. First, investment in nuclear energy and sequestration continue. Nuclear plants are under construction in China, South Korea, and elsewhere, and are approaching completion in the states of Georgia, Tennessee, and South Carolina in the United States. If the commissioning of these new plants goes smoothly, the rate of plant starts could grow. Also, SaskPower in Saskatchewan, Canada, recently commissioned an entire unit within the Boundary Dam coal-fired power plant to divert by-product CO_2 to sequestration. Again, if this system is successful, it could be reproduced elsewhere.

Another factor is that all three primary sources continue to be significant contributors to overall world demand, and this situation cannot change instantly. Fossil fuels stand at 82% of the market by energy content, down from 85% in 1990 but still the dominant source by far. Nuclear is still larger than any one renewable source, including hydropower, wind, or solar. As long as all sources continue to contribute, it is beneficial to compare them side by side in the context of a book on energy systems.

A third premise is that *where long-term technologies will take time to develop fully, there is value to developing "bridge" technologies for the short-to-medium term*. Some of the technologies presented in this book eliminate harmful emissions or use only renewable resources, but will take time to deploy, due to the slow nature of infrastructure transitions. In this situation, there is value to bridge technologies that are cost-effective now and also reduce nonrenewable resource consumption or CO_2 emissions, even if they do not eliminate them entirely. Typically, these technologies consume fossil fuels but are more efficient or have higher utilization, so that they deliver more energy service per unit of resource consumed or CO_2 emitted.

Although the book is written by American authors in the context of the U.S. energy system, we maintain an international focus. This is important because of the increasingly global nature of the energy industry, in terms of both the resource base and the transfer of technology between countries. We hope that non-U.S. readers of the book will find the material accessible, and that U.S. readers can apply the content to energy projects in

For simplicity, all costs are given in dollars; however, other world currencies can of course be substituted into equations dealing with financial management.

Both a systems approach and an engineering economics approach to designing and costing projects are emphasized. The use of good systems engineering techniques, such as the systematic consideration of the project scope, evaluation of tradeoffs between competing criteria, and consideration of project life-cycle cost and energy consumption, can deliver more successful projects. Consideration of the cost of and revenues from a project, as well as technical efficiency, helps us to better understand the profitability of a project.

For the purposes of cost analysis, approximate prices for the cost of energy resources and the purchase of energy conversion equipment have been introduced in places at their appropriate values. These values are intended to give the reader a general sense of the financial dimensions of a technology, for example, approximately what proportion of an energy technology's life-cycle cost is spent on fuel versus capital or nonfuel operating costs. Note, however, that theses values should not be used as a basis for detailed decision making about the viability of a project, since up-to-date costs for specific regions are the required source. It is especially important to find up-to-date numbers for one's particular project of interest because of the volatility in both energy and raw material prices that has developed since 2004 or 2005. With rapid economic growth in the two largest countries by population in the world, namely China and India, there is burgeoning demand not only for energy commodities but also for materials such as steel or copper that are essential for fabricating energy conversion technologies. This affects not only operating costs of fossil-fuel-driven energy systems but also capital cost of both renewable and nonrenewable energy systems. To give a concrete example from Chap. 5, oil prices were at or below $20/barrel up to 2005, then fluctuated between $80 and $140 per barrel for most of the period 2008–2014, and finally fell to the range of $30–$50/barrel in the period from 2014 on. It is thus difficult to predict what will happen next.

Earlier books on energy systems have placed an emphasis on equipment to prevent release of air pollutants such as scrubbers or catalytic converters. As presented in the body of this book, emerging technologies that use new energy resources and eliminate CO_2 emissions also tend to eliminate emissions of harmful air pollutants, so air quality as a separate objective is deemphasized here. In some cases, it appears instead as a constraint on energy systems development: where air quality problems may be aggravated by emerging technologies that are beneficial for other objectives but increase emissions of air pollutants, regulations or targets related to air quality may restrict our ability to use that technology.

In conclusion, we offer a word of "truth in advertising" about the contents of the book: it provides some answers, and also many unanswered questions. It is humbling to write a book about energy systems, just as it is to teach a course or give a presentation about them: one ends up realizing that it is a very challenging area, and that many aspects of future solutions remain hidden from us at present. We hope that in publishing this book, we have helped to answer some of the questions about energy systems where possible, and, where not, posed them in such a way that the act of exploring them will move the field forward. The extent and complexity of the challenge may seem daunting at times, yet there are and will be great opportunities for energy professionals, both now and in the future. We wish each of you success in your part of this great endeavor.

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CHAPTER 1

Introduction

1-1 Overview

The purpose of this chapter is to introduce the engineer to the worldwide importance of energy systems, and to the historic evolution of these systems up to the present time. We discuss how energy use in various countries is linked to population and level of economic activity. Next, we consider current trends in total world energy use and energy use by different countries, and discuss how the pressure from growing energy demand and growing CO_2 emissions poses a substantial challenge for the world in the coming years and decades. Thereafter, we present an overview of how a *sustainable* world energy situation might appear at some point in the mid to latter part of the twenty-first century, including contributions from different energy resources, and allocation to major end uses. We also provide a *road map* for how the chapters in the book contribute to the understanding needed for the success of this sustainable energy solution. The chapter concludes with a review of basic units used to measure energy in the metric and U.S. customary systems.

1-2 Introduction

When an energy engineer[1] thinks of access to energy or energy systems, whether as a professional responsible for the function of some aspect of the system, or as an individual consumer of energy, a wide range of applications come to mind. These applications include electricity for lighting or electronics, natural gas for space heating and industrial uses, and petroleum products such as gasoline or diesel for transportation. Access to energy in the industrialized countries of Asia, Europe, and North America is so pervasive that consumption of energy in some form is almost constant in all aspects of modern life—at home, at work, or while moving from place to place. In the urban areas of industrializing and less-developed countries, not all citizens have access to energy, but all live in close proximity to the local power lines and motorized vehicles that are part of this system. Even in the rural areas of these countries, people may not be aware of modern energy systems on an everyday basis, but may come into occasional contact with them through access to food shipments or the use of rural bus services. Indeed, there are very few human beings who live in complete isolation from this system.

If it is true that use of energy is omnipresent in modern life, then it is also true that both individuals and institutions (governments, private corporations, universities,

[1]The term "energy engineer" is used here to refer both to readers with formal engineering training and those without formal training who are interested in understanding and implementing energy systems.

schools, and the like) *depend* on reliable access to energy in all its forms. Without this access, the technologies that deliver modern amenities including comfortable indoor temperature, safe food products, high-speed transportation, and so on, would quickly cease to function. Even the poorest persons in the less-developed countries may rely on occasion for their survival on shipments of food aid that could not be moved effectively without mechanized transportation.

In order for an energy resource to be reliable, it must, first of all, deliver the service that the consumer expects. Second, it must be available in the quantity desired, when the consumer wishes to consume it (whether this is electricity from a wall outlet or gasoline dispensed from a filling station). Lastly, the resource must be available at a price that is economically affordable.

The above qualities define the reliability of the energy resource, for which the consumer will experience adverse consequences if not met—immediately, if the energy system or device stops functioning correctly, or within a short period of time, if the price of the resource is unaffordable. Longer term, there is another criterion for the energy resource that must be met, and one for which society as a whole suffers negative consequences, even if the individual user does not experience consequences directly from her or his actions and choices: environmental sustainability. At the beginning of the twenty-first century, this dimension of energy use and energy systems is increasingly important. Practices that may have placed negligible stress on the planet 100 or 150 years ago, simply because so few people had access to them, are no longer acceptable today, when billions of human beings already have access to these practices or are on the verge of achieving sufficient wealth to have access to them. Thus the need to deliver energy in a way that is both *reliable* and *sustainable* places before humanity a challenge that is both substantial and complex, and one that will require the talent and efforts of engineers as well as research scientists, business managers, government administrators, policy analysts, and so on, for many years, if not decades, to come.

1-2-1 Historic Growth in Energy Supply

Looking back at how humanity has used energy over the millennia since antiquity, it is clear that the beginning of the industrial revolution marks a profound change from gradual refinement of low-power systems to rapid advances in power-intensive systems of all sorts. Along with this acceleration of evolution came a rapid expansion of the ability of human beings to multiply their maximum power output through the application of technology.

Of course, ever since the dawn of recorded history, it has been human nature to improve one's quality of life by finding alternatives to the use of human force for manipulating and moving objects, transforming raw materials into the necessities of life, and conveying oneself between points A and B. The earliest *technologies* used to these ends include the use of horses and other draft animals for mechanical force or transportation, and the use of water currents and sails for the propulsion of boats, rafts, and other watercraft. Over time, humans came to use wood, charcoal, and other *biofuels* for space heating and "process heat," that is, heat used for some creative purpose such as cooking or metallurgy, for various activities. The sailboat of the ancient Mediterranean cultures evolved into the sophisticated sail-rigging systems of the European merchant ships of the 1700s; in Asia, Chinese navigators also developed advanced sail

the combustion of plants grown on the Earth's surface for providing heat, and efforts to mine coal were expanding in European countries, notably in Britain.

The evolution of wind power for mechanical work on land prior to 1800 illustrates the gradual refinement of a technology prior to the industrial revolution. The earliest *windmills* in the Middle East used the force of the wind against a vertical shaft to grind grain. Later, the rotation around a horizontal axis was adopted in the *jib mill* of Crete and other Mediterranean locations. Jib mills also used removable "sails" on a hollow wooden frame of the mill "wing" so that the operator could adjust the amount of surface area to the availability of wind, and especially protect the mill from excessive force on a windy day by operating the mill with only part of the wing cover. Several more centuries brought the advent of the windmill that could be rotated in response to the direction of the wind. At first, it was necessary to rotate the entire mill structure around its base on the ground in order to face into the wind. A later refinement was the rotating mill in which only the top "turret" of the mill turned (specimens of which are still seen today in the Netherlands, Belgium, and Northern France), while the rest of the structure was affixed permanently to its foundation. This entire evolution took place over approximately 1000 years.

Compared to this preindustrial evolution, changes have taken place much more rapidly since 1800. In short order, water and wind power gave way to steam power, which in turn has given way to the ubiquitous use of the electric motor and electric pump in all manner of applications. On the transportation side, the two centuries since 1800 have seen the rise of the steam-powered water vessel, the railroad, the internal combustion engine, the automobile, the airplane, and ultimately the spacecraft. Along the way, the use of electricity not only for transmitting energy but also for storing and transmitting information has become possible.

A comparison of two events from antiquity with events of the present age illustrates how much has changed in the human use of energy. In the first event, the Carthaginian army under General Hannibal met and defeated the Roman army under General Paulus at Cannae, to the east of modern day Naples on the Italian peninsula, in the year 216 BC.[2] On the order of 100,000 men and 10,000 horses took part in this battle on both sides. At around the same time, Emperor Qin Shihuang ordered the construction of the Great Wall of China, which required approximately 10 years around the year 200 BC. This project is thought to have involved up to 300,000 men at a time using manual labor to assemble materials and erect the wall.

An "energy analysis" of either of these endeavors, the battle or the building project, reveals that in both cases, the maximum output of even such a large gathering of men and horses (in the case of Cannae) is modest compared to that of a modern-day energy system. For purposes of this analysis, we use a metric unit of power, the *watt* (abbreviated W), that is defined in Sec. 1-6-1. Using a typical figure for long-term average output of 70 W or 200 W for either a human body or a horse, respectively, one can estimate the output at Cannae at approximately 9×10^6 W, and at the Great Wall at approximately 2.1×10^7 W.[3] By comparison, a modern fossil- or nuclear-fired power

[2]This example is due to Lorenzo (1994), p. 30, who states that the average output for a horse was much less than a modern "horsepower" due to the lack of horseshoes.

[3]Note that these figures are significantly less than the maximum instantaneous output of either human or horse, for example in the case of a laborer exerting all his strength to lift a stone into position in the Great Wall. Inability to sustain a high instantaneous output rate is in fact one of the main limitations of

plant in China, Italy, or any other industrial country can deliver 5×10^8 W or more uninterrupted for long periods of time, with a crew of between 10 and 50 persons only to maintain ongoing operations. Similarly, a string of four or five modern railroad locomotives pulling a fully loaded train up a grade can deliver between 4×10^7 W of power with a crew of just three persons.

Two further observations on this comparison between the ancient and the modern are in order. First, if we look at the growth in maximum power output per human from 70 W in 200 BC to a maximum of approximately 5×10^7 W in 2000 for a power plant—six orders of magnitude—we find that most of the advancement has come since the year 1800. Some part of the scientific understanding necessary for the subsequent inventions that would launch the modern energy system came prior to this year, during the advances of Chinese scientists in the preceding centuries, or the Renaissance and Age of Enlightenment in Europe. However, most of the actual engineering of these energy technologies, that is, the conversion of scientific understanding into productive devices, came after 1800. Second, having created a worldwide, resource-intensive system to convert, distribute, and consume energy, human society has become *dependent* on a high rate of energy consumption and cannot suddenly cut off all or even part of this energy consumption without a significant measure of human stress and suffering. For example, a modern office high-rise in any major metropolis around the globe—Sao Paulo, New York, London, Johannesburg, Dubai, Hong Kong, or Sydney, to name a few—is both a symbol of industrial strength and technological fragility. These buildings deliver remarkable comfort and functionality to large numbers of occupants, but take away just three key inputs derived from energy resources—electricity, natural gas, and running water—and they become uninhabitable.

1-3 Relationship between Energy, Population, and Wealth

Changes in levels of energy consumption, both for individual countries and for the world as a whole, are in a symbiotic relationship with levels of both population and wealth. That is, increasing access to energy makes it possible for human society to support larger populations and increasing levels of wealth, while at the same time, a growing population and increasing wealth will spur the purchase of energy for all aspects of daily life.

A comparison of estimates of world population and energy production [measured in either joules (J) or British thermal units (BTUs)—see Secs. 1-6-1 and 1-6-2, respectively] from 1850 to 2010 is shown in Fig. 1-1. The growth in world energy production intensity per capita, or amount of energy produced per person, is also shown, measured in either billion joules per capita, or million BTU per capita. The values shown are the total energy production figures divided by the population for each year. While population growth was unprecedented in human history over this period, growing nearly fivefold to approximately 6 billion, growth in energy consumption was much greater, growing more than twentyfold over the same period.

From analysis of Fig. 1-1, the energy production growth trend can be broken into five periods, each period reflecting events in worldwide technological evolution and social change. From 1850 to 1900, industrialization and the construction of railroad networks was underway in several parts of the world, but much of the human population did not yet have the financial means to access manufactured goods or travel

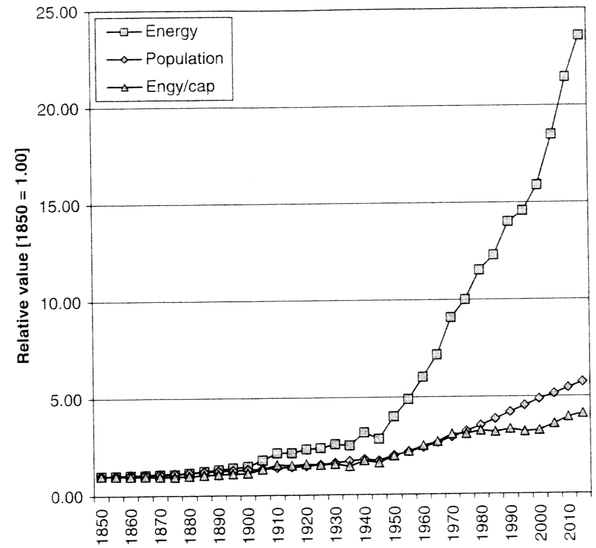

Figure 1-1 Relative growth in world population, world energy production, and average energy production per capita 1850–2015, indexed to 1850 = 1.00.

Notes: In 1850, population was 1.26 billion, energy was 25 exajoules, abbreviated EJ, or 23.7 quadrillion BTU, or quads, and per capita energy use was 19.8 gigajoules, abbreviated GJ, per person or 18.8 million BTU per person.[4] For all data points, energy per person is the value of the energy curve divided by the value of the population curve; see text. Total energy and energy per capita figure for 2015 based on 2013 observed figure of 568 EJ and extrapolation of 2010–2013 energy consumption trend out to 2015, resulting in 2015 value of 589 EJ. 2015 population figure is 7.214 billion people according to United Nations. (*Sources:* Own calculations based on energy data from Energy Information Administration of the U.S. Department of Energy and population data from U.S. Bureau of the Census.)

and energy production grew roughly in line with population. From 1900 to 1950, both the part of the population using modern energy supplies and the diversity of supplies (including oil and gas as well as coal) grew, so that energy production began to outpace population and energy intensity per capita doubled by 1950, compared to 1850. From 1950 to 1975, energy production and energy intensity grew rapidly in the post–World War II period of economic expansion. From 1975 to 2000, both energy and population continued to grow, but limitations on output of some resources for energy, notably crude oil, as well as higher prices, encouraged more efficient use of energy around the world, so that energy production per capita remained roughly constant.

[4]In other words, 1 EJ = 10^{18} joules, 1 GJ = 10^9 joules. See Sec. 1-6 on energy units at the end of this

Finally, from 2000 to 2015, global per capita energy use has increased slightly, led by industrializing countries such as China that saw rapid growth in energy consumption after the year 2000.

It is difficult to extrapolate from the time series data in Fig. 1-1 what will happen over the next 25 or 50 years. On one hand, the absolute magnitude of energy production is growing at the present time and may continue to grow for the foreseeable future. On the other hand, with rapid increase in awareness in both industrialized and industrializing countries of the problems of continuing rapid increase in global energy consumption, we may at some point see the effects of policies aimed at dramatically improving energy efficiency so that more of the world's people can have access to the benefits of energy without the continued rapid rise of total energy consumption.

1-3-1 Correlation between Energy Use and Wealth

The most commonly used measure of wealth at present is the gross domestic product, or GDP, which is the sum of the monetary value of all goods and services produced in a country in a given year. For purposes of international comparisons, these values are usually converted to U.S. dollars, using an average exchange rate for the year. In some instances, the GDP value may be adjusted to reflect purchasing power parity (PPP), since even when one takes into account exchange rates, a dollar equivalent earned toward GDP in one country may not buy as much as in another country (e.g., in the decade of the 1990s and early 2000s, dollar equivalents typically had more purchasing power in the United States than in Japan or Scandinavia).

Though other factors play a role, the wealth of a country measured in terms of GDP per capita is to a fair extent correlated with the energy use per capita of that country. In recent data, both the GDP per capita and per capita energy consumption vary by one to two orders of magnitude between the countries with the lowest and highest values. Consider three countries, namely, Bahrain, the United States, and Zimbabwe, using 2011 data. For GDP per capita, the values are $1131 per person for Zimbabwe versus ~$55,900 per person for the United States, not adjusting for PPP. For energy, they are 14.3 GJ/person (13.5 million BTU/person) for Zimbabwe, versus 476 GJ/person (451 million BTU/person) for Bahrain. Table 1-1 presents a subset of the world's countries including Bahrain, the United States, and Zimbabwe, selected to represent varying degrees of wealth as well as different continents of the world, to illustrate the connection between wealth and energy.

Plotting these countries' GDP per capita as a function of energy use per capita (see Fig. 1-2) shows that GDP per capita rises with energy per capita, especially if one excludes countries such as Russia and Bahrain, which may fall outside the curve due to their status as major oil producers or due to extreme climates. Also, among the most prosperous countries in the figure, namely, those with a per capita GDP above $30,000 (Germany, Australia, Japan, Canada, and the United States), there is a wide variation in energy use per capita, with U.S. and Canadian citizens using on average about twice as much energy as those of Japan or Germany.

1-3-2 Human Development Index: An Alternative Means of Evaluating Prosperity

In order to create a measure of prosperity that better reflects broad national goals beyond the performance of the economy, the United Nations has, since the early 1990s,

Country	Population (millions) 2004	Population (millions) 2011	Energy (EJ) 2004	Energy (EJ) 2011	GDP (billion US$) 2004	GDP (billion US$) 2011
Australia	20.2	21.8	6.0	6.5	699.7	1444.2
Bahrain	0.7	1.2	0.5	0.6	11.7	33.9
Brazil	186.4	197.6	10.6	12.5	804.5	2353.0
Canada	32.3	34.0	15.1	14.1	1131.5	1788.7
China	1315.8	1336.7	47.7	109.4	2240.9	10,380.4
Gabon	1.4	1.6	0.1	0.1	9.0	17.2
Germany	82.7	81.5	17.3	14.2	2805.0	3859.5
India	1103.4	1189.2	15.4	24.8	787.8	2049.5
Israel	6.7	7.5	0.9	1.1	122.8	303.8
Japan	128.1	127.5	26.4	22.1	4583.8	4616.3
Poland	38.5	38.4	4.3	4.3	303.4	546.6
Portugal	10.5	10.8	1.3	1.1	183.0	230.0
Russia	143.2	142.5	33.9	32.1	768.8	1857.5
Thailand	64.2	66.7	3.5	5.2	165.5	373.8
United States	298.2	311.6	116.8	102.8	12,555.1	17,418.9
Venezuela	26.7	27.6	3.5	3.4	134.4	205.8
Zimbabwe	13.0	12.1	0.3	0.2	3.9	13.7

Note: GDP values in current dollars.

Sources: UN Department of Economics and Social Affairs (2006) and Population Reference Bureau (2015), for population; U.S. Energy Information Administration (2015), for energy use; International Monetary Fund (2015), for economic data.

TABLE 1-1 Population, Energy Use, and GDP of Selected Countries, 2004 and 2011

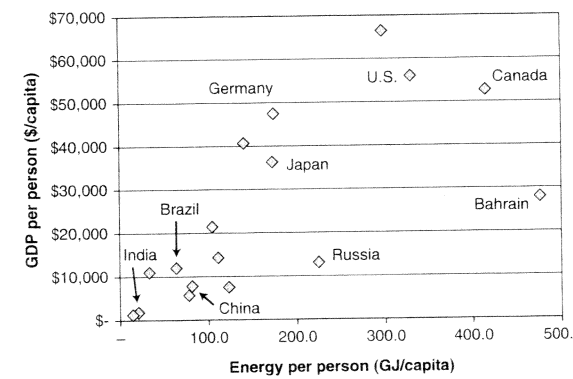

FIGURE 1-2 Per capita GDP as a function of per capita energy consumption in gigajoules (GJ) per person for selected countries, 2011.

Note: Conversion is 1 million BTU = 1.055 GJ. *Sources:* UN Department of Economics and Social Affairs (2015), for population; U.S. Energy Information Administration (2015), for energy consumption;

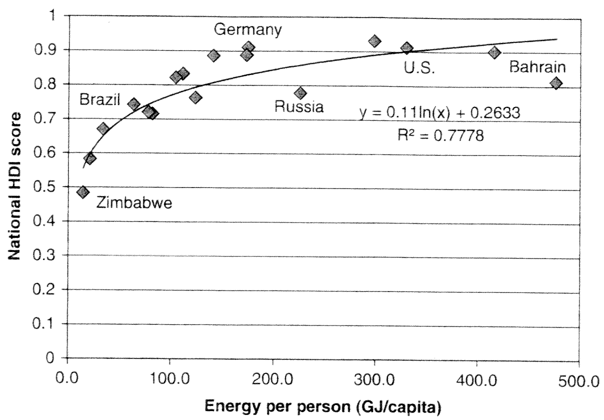

FIGURE 1-3 Human development index as a function of per capita energy consumption in GJ per person for selected countries, 2011.

scale from 0 (worst) to 1 (best),[5] and is an average of the following three general indices for life expectancy, education, and GDP per capita:

$$\text{Life expectancy index} = (\text{LE}-25)/(85-25) \tag{1-1}$$

$$\text{Education index} = 2/3(\text{ALI}) + 1/3(\text{CGER}) \tag{1-2}$$

$$\text{CGER} = 1/3(\text{GER Prim} + \text{GERSecond} + \text{GERTerti}) \tag{1-3}$$

$$\text{GDP index} = \frac{[\log(\text{GDPpc}) - \log(100)]}{[\log(40000) - \log(100)]} \tag{1-4}$$

In Eqs. (1-1) to (1-4), LE is the average life expectancy in years; ALI is the adult literacy index, or percent of adults that are literate; CGER is the combined gross enrollment rate, or average of the primary, secondary, and tertiary gross enrollment rates (i.e., ratio of actual enrollment at each of three educational levels compared to expected enrollment for that level based on population in the relevant age group);[6] and GDPpc is the GDP per capita on a PPP basis.

As was the case with GDP per capita, plotting HDI as a function of energy use per capita (see Fig. 1-3) shows that countries with high HDI values have higher values of energy use per capita than those with a low value. For example, Zimbabwe, with a life expectancy of 59 years and an HDI value of 0.484, has an energy per capita value of 14.3 GJ/capita or 13.5 million BTU/capita, whereas for Canada, the corresponding

[5]In the future, it may be necessary to adjust benchmark life expectancy and GDP per capita values in order to prevent the HDI from exceeding a value of 1 for the highest ranked countries.

[6]For example, suppose a country has a population of age to attend primary school (approximately ages

values are 0.950, 4.7×10^{11}, and 442, respectively. Also, among countries with a high value of HDI (> 0.80), there is a wide range of energy intensity values, with Bahrain consuming 476 GJ/capita (451 million BTU/capita) but having an HDI value of 0.813, which is somewhat lower than that of Canada.

1-4 Pressures Facing World due to Energy Consumption

As shown in Fig. 1-1, world energy consumption increased dramatically between 1950 and 2015, from approximately 100 EJ to over 500 EJ. This trend continues at present due to ongoing expansion in consumption of energy. Many wealthy countries have slowed their growth in energy consumption compared to earlier decades, notably countries such as Japan or the members of the European Union. Some countries have even stabilized their energy consumption, such as Denmark, which consumed 0.92 EJ (0.86 quad) in 1980 and 0.78 EJ (0.74 quad) in 2012. Such countries are in a minority, especially since it is the emerging economies of the developing world where demand for energy is growing most rapidly. In these countries, a historical transformation is under way: as their economies grow wealthier, they adopt many of the features of the wealthy countries such as the United States, Japan, or Canada, and their per capita energy consumption therefore approaches that of the wealthy countries.

1-4-1 Industrial versus Emerging Countries

The data in Fig. 1-4, which include all gross energy consumption such as energy for transportation, conversion to electricity, space heating and industrial process heat, and as a raw material, illustrate this point. In the figure the countries of the world are grouped into either the "industrial" category, which includes the European Union and Eastern Europe, North America, Japan, Australia, and New Zealand, or an "emerging"

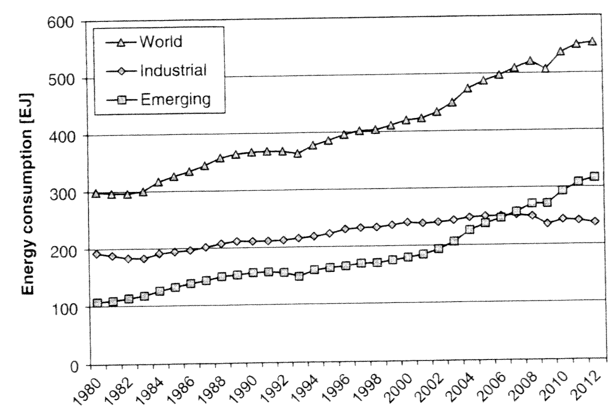

FIGURE 1-4 Comparison of total energy consumption of industrial and emerging countries, 1980–2012.

category, which includes all other countries. This division is made for historical reasons, because at the beginning of the expansion in energy use in 1950, the countries in the industrial category were generally considered the *rich* countries of the world. Today, some of the emerging countries have surpassed a number of the industrial countries in GDP per capita or energy use per capita, such as South Korea, which has passed all the countries of the former Eastern European bloc (Czech Republic, Poland, and others) in both measures. In any case, thanks to their faster growth rate since approximately 2000, the emerging countries overtook the industrial countries in 2007, even as both groups of countries followed the ups and downs of global economic trends (e.g., slower growth in periods of relative economic weakness such as the early 1980s, early 1990s, early 2000s, or recession of 2009-2010). In 2012, the emerging countries consumed 316 EJ (299 quads) versus 237 EJ (225 quads) for the industrial countries.

Furthermore, a comparison between total energy use and total population for the two groups of countries suggests that the total energy use for the emerging countries might grow much more in the future. The industrial countries comprise approximately 1.4 billion people, with the emerging countries representing the remaining 5.3 billion people on the planet (2008 values). On this basis, the industrial countries consume more than three times the energy per capita than emerging countries. If, in the future, the economies of the emerging countries were to grow to resemble those of the industrial economies, such that the per capita energy consumption gap between the two were to be largely closed, total energy for the emerging countries might exceed that of the industrial group by a factor of 2 or 3.

To further illustrate the influence of the industrial and emerging countries on world energy consumption, we can study the individual energy consumption trends for a select number of countries that influence global trends, as shown in Fig. 1-5. The "countries" include an agglomeration of 38 European countries called "Europe38," which consists of

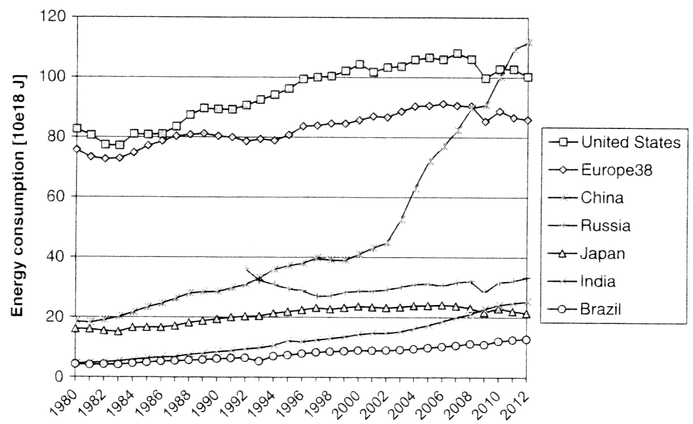

Figure 1-5 Comparison of select countries total energy consumption, 1980–2012.
Note: Russia's trend line appears in year 1992 because in prior years its energy consumption

38 countries from Western and Eastern Europe, but not the former Soviet Union. The other countries included are the United States, Japan, China, Russia, India, and Brazil.[7] Together, the countries represented in the figure account for 71% of the world's energy consumption in 2012.

Two important trends emerge from Fig. 1-5. First, among the rich countries represented, energy consumption growth in the United States outpaces that of Europe38 and Japan, so that the United States is becoming an increasingly dominant user of energy among this group. In the late 1980s, the United States and Europe38 were almost equal in terms of energy use, but energy use in Europe has grown more slowly since that time, measured either in percentage or absolute magnitude. Second, the percent growth rate, and absolute magnitude in the case of China, is much higher for China, Brazil, and India from 2002 onward than for the other countries in the figure. These three countries grew by 101%, 24%, and 43%, respectively, during this time period. Particularly, striking was the growth of energy consumption in China by some 45 EJ (43 quads) in the period from 2002 to 2008 alone; this spike in energy consumption was enough to visibly affect the trend in world energy consumption in Fig. 1-4. This trend reflects the transformation of the Chinese economy from that of a low-cost industrial producer to that of a modern consumer economy, similar to that of the rich countries, as symbolized by the two photographs in Fig. 1-6.

The energy growth path of China can be viewed from a different perspective by comparing it to that of the United States in terms of the annual growth since reaching a threshold of 40 quads of gross energy consumption, as shown in Fig. 1-7. The United States reached this threshold in 1955 and China in 2001. The figure shows the subsequent growth pathway, where the horizontal axis gives the number of years elapsed since 1955 or 2001, depending on the country, and the vertical axis gives the total energy consumption in that year. For the United States, growth from 40 to 90 quads required 40 years (1955–1995). In the case of China, this growth took place over a period of just 8 years (2001–2009).

While growth in energy use in China may be rapid, especially recently, the per capita value remains lower than that of industrialized countries. In 2011, the average person in China consumed 82 GJ (78 million BTU), compared to 330 GJ (313 million BTU) for the average person in the United States. Figure 1-8 illustrates the trend for China, the United States, and five other countries for the period 1980–2011: while per capita energy consumption for China has risen markedly since 2000, it remains well below that of Japan, the United Kingdom, Russia, and especially the United States.

The preceding data suggest that, for rapidly growing countries like China, Brazil, and India, there is much room for both total energy consumption and energy consumption per capita to grow. Recall also the strong connection between energy use and GDP. Whereas the industrial countries typically grow their GDP 2–3% per year, China's economy has been growing at 7–10% per year in recent years. The values in 2011 of $7.8 trillion GDP and $7766 per capita for China, compared to $17.4 trillion and $55,900, respectively, for the United States, indicate that there is much room for GDP and GDP per capita in China to grow, barring some major shift in the function of the world's economy. This growth is likely to continue to put upward pressure on energy consumption in China.

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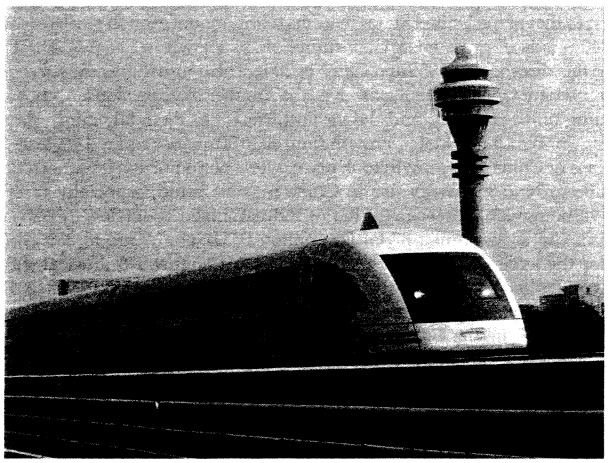
[7]Brazil, Russia, India, and China are included in the figure because they comprise the four "BRIC" countries, which represent a large fraction of the world's energy consumption, population, and

(a)



(b)

FIGURE 1-6 An example of rapid technological transformation in China.

Figure 1-6(a) shows a Chinese steam locomotive in regular service, Guangdong Province, 1989. Figure 1-6(b) shows a Maglev train in Shanghai, 2006. Just 17 years separate these two photographs. Although the adoption of modern technology has generally increased energy consumption in China, it has also increased efficiency in some cases, as happened with the phasing out of the use of inefficient steam locomotives by the mid-1990s. [*Source:* Jian Shuo Wang, wangjianshuo.com (Fig. 1-6b). Reprinted with permission.]

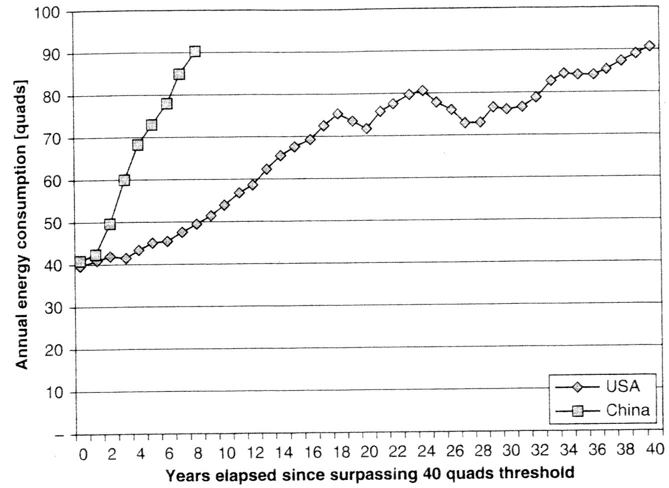


FIGURE 1-7 40 to 90 quads in 8 years? Figure of annual energy consumption for China and the United States for the number of years required to grow from 40 to 90 quads of total energy. Year 0 in the figure is equivalent to the years 2001 and 1955 for China and the United States, respectively.

(*Source:* U.S. Energy Information Administration.)

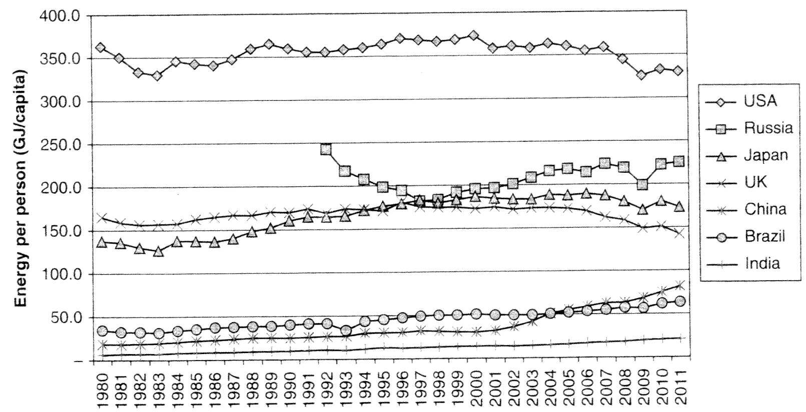


FIGURE 1-8 Per capita energy consumption for select industrialized and BRIC countries, 1980–2011.

Note: Russia trend line appears in year 1992 because in prior years its energy consumption was part of former Soviet Union. Per capita energy use in the United Kingdom is used to represent typical values for

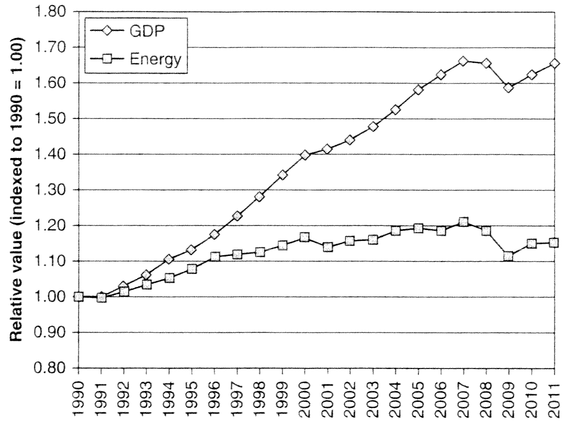


FIGURE 1-9 Relative values of energy use and real GDP in the United States indexed to 1990 = 1.00, 1990–2011. In 1990, the value of GDP in 2005 dollars was $8.0 trillion, and the value of energy consumption was 89.3 EJ (84.6 quads). [*Source:* U.S. Energy Information Administration.]

At the same time, there is another trend emerging in the industrial countries such as the United States that is more promising in terms of energy supply and demand, namely the potential breaking of the link between GDP and energy. Figure 1-9 shows U.S. real GDP (in constant 2005 dollars)[8] and U.S. gross energy consumption trend indexed to the value 1993 = 1.00. From the year 1996 onward, the two trends diverge with real GDP continuing to grow rapidly (43% over the period 1996–2011), while growth in energy slows (just 3% over the same period). A number of factors may have contributed to this situation, including the rise of the information economy (which may generate wealth with relatively less use of energy), the use of telecommuting in place of physical travel to work, the effect of more efficient technology on industrial and residential energy use, the departure of energy-intensive manufacturing to overseas trading partners[9] and so on. It is possible that countries such as China may soon reach a point where they too can shift to a path of economic growth that does not require major increase in energy consumption. One must be careful, however, not to overstate the significance of the trend since 1996. It is possible that the break between GDP and energy is temporary and that future values will show a return to a closer correlation between energy and GDP; furthermore, even in the period 1996–2011, the value of energy use per capita for the United States is very high and could not be sustained if it were applied to the world's population of nearly 7 billion, given current technology.

[8]The distinction between "constant" and "current" dollars is as follows: An amount given in current dollars is the face value of the dollar amount in the year in which it is given; an amount given in constant dollars has been adjusted to reflect the declining purchasing power of a dollar over time. For example, the 1993 and 2000 U.S. GDP in current dollars was $6.66 billion and $9.82 billion, respectively. However, the value of the dollar in 2000 was 88% of a 1993 dollar, so adjusting the GDP values to 2000 constant dollars gives $7.53 and $9.82 billion, respectively. See Chap. 3.

[9]Caveat: If, in fact, the shifting of manufacturing overseas was shown to be the main contributor to the slowdown in the growth of energy consumption in the USA, it could be argued that in fact there is no breaking of the link between GDP and energy growth, since the energy consumption would still be

1-4-2 Pressure on CO_2 Emissions

Negative effects of energy use do not come directly from the amount of gross energy consumption itself, but rather from the amount of nonrenewable resources consumed in order to deliver the energy, the side effects of extracting energy resources, the total emissions of pollution and greenhouse gases emitted from the use of that energy, and so on. We can examine the case of CO_2 emissions by looking at the trend for these emissions for industrial and emerging countries, as shown in Fig. 1-10. In the figure, the industrial countries are divided into "North America" (i.e., Canada and the United States, but not Mexico), Europe38, and "Other Industrial" (Japan, Australia, and New Zealand), while the emerging countries are divided between the four BRIC countries and "Rest of World"(ROW), or all remaining countries in the world not previously included. The pattern is similar to the one for energy consumption shown in Fig. 1-4, with emissions from the ROW, and especially BRIC countries, growing faster than those for the industrial countries from approximately 2000 onward. The emerging countries also surpassed the industrial countries sooner in terms of CO_2 emissions compared to energy consumption, with these two events taking place in the years 2003 and 2007,

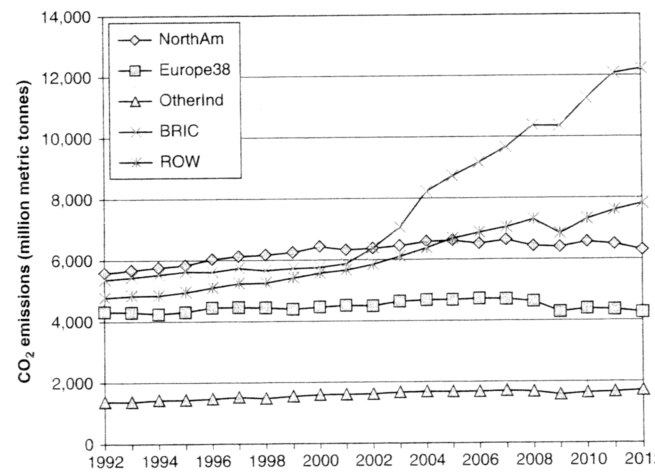


FIGURE 1-10 Carbon dioxide emissions for North American, European, other industrial, BRIC, and ROW countries, 1992–2008.

Note: Other industrial countries include Japan and Oceania. Rest of world includes all countries not in previous four groups. (*Source:* U.S. Energy Information Administration.)

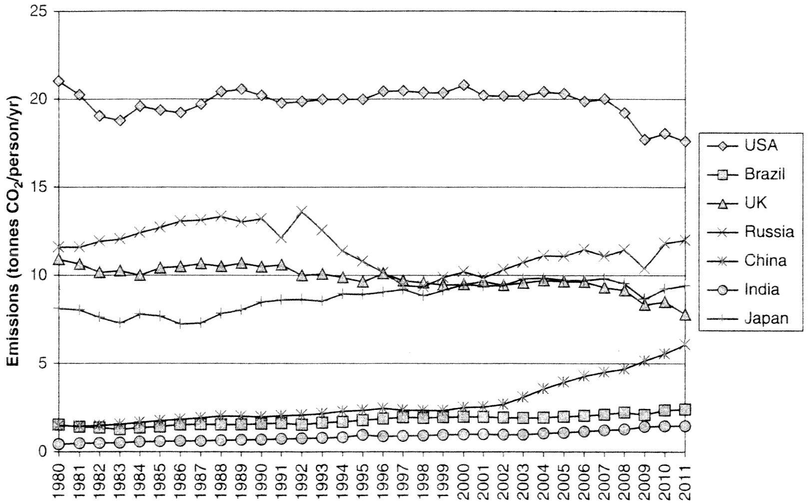


FIGURE 1-11 Per capita CO_2 emissions for select countries, 1980–2011. [*Source:* U.S. Energy Information Administration.]

respectively. Another way of saying this is that the industrial countries emit less CO_2 per unit of energy consumed (in 2012, 52 kg/GJ, versus 64 kg/GJ for the emerging countries). The industrial countries have an advantage both because they convert energy resources to energy products more efficiently, and because they have greater access to low- and zero-CO_2 energy resources.

At the worldwide level, emissions of CO_2 per GJ of energy consumed declined slightly from 1980 to 2012, by about 6% (62 versus 58 kgCO_2 per GJ), using the data from Figs. 1-4 and 1-10. Worldwide emissions of CO_2 per capita increased slightly from 1980 to 2011, from 4.0 to 4.6 tonnes per person per year, after doubling between 1950 and 1980.[10]

Per capita CO_2 emissions trends for select industrial and emerging countries are shown in Fig. 1-11. The BRIC countries show growing per capita emissions since 2000, with China in particular showing a large rise due to both growing industrial output for domestic and global markets and a growing middle class. Although it is not as easy to discern due to the scale of the figure, Brazil and India also grew in per capita emissions by 25% and 50%, respectively, and Russian per capita emissions grew as well. U.S. and European emissions (represented by the United Kingdom as a typical European energy user) declined on the other hand. Among the industrial countries only emissions in

[10]See Marland et al. (2003) for comparison of 1950 and 1980: ~2.4 metric tonnes of CO_2 equivalent in 1950, 4.5 tonnes in 1980.

Japan actually increased from 1998 to 2011, influenced by the closure of nuclear power plants after the Fukushima accident in 2011.

In conclusion, trends in Figs. 1-10 and 1-11 suggest that there is reason for great concern regarding CO_2 emissions in the short to medium term. While the value of CO_2 per unit of energy or per capita may be more or less stable—possibly increasing slightly, but not substantially—it is still high for a planet that needs to dramatically cut greenhouse gas emissions. Furthermore, since both total energy use and total world population are climbing, total CO_2 emissions will climb with them if steps are not taken to decrease CO_2 per unit of energy or per capita.

1-4-3 Observations about Energy Use and CO_2 Emissions Trends

Two observations round out the discussion of energy and CO_2. The first observation is in regard to the distinct roles of the industrial and emerging countries in addressing the energy challenges of the present time. At first glance, it might appear from Fig. 1-4 that the emerging countries are not doing as much as the industrial countries in using energy as efficiently as possible, and from Fig. 1-5 that China in particular is not doing its part to address the sustainable use of energy. This type of thinking is incomplete, however. Countries such as China, and the emerging countries in general, consume much less energy per capita than do the industrial countries (Fig. 1-8). Therefore, in creating a global solution for energy, the countries of the world must recognize that while one factor is a sustainable overall level of energy use, another factor is the right of emerging countries to expand their access to energy in order to improve the everyday well-being of their citizens. A possible solution is one in which the industrial countries greatly increase their efficiency of energy use so as to decrease both energy use and CO_2 emissions per capita, while the emerging countries work toward achieving a quality of life equal to that of the industrial countries, but requiring significantly less energy and CO_2 emissions per capita than the current values for the industrial countries.

The second observation is in regard to the overall trend in energy and CO_2 emissions and how best it should be addressed. Looking at Figs. 1-4, 1-5, 1-10, and 1-11, it is clear that the growth in energy consumption and CO_2 emissions has been continuous over many years. Even though the industrial countries appear to be curbing their growth since approximately 2008, emerging countries are in a position to continue to push the trend upward. A key factor is therefore to enable increased energy use without increasing negative impact on the environment through technology. It will be shown in this book that a great deal of physical potential exists to deliver energy in the substantial amounts needed, and without emitting correspondingly large amounts of CO_2 to the atmosphere, using sources that we already understand reasonably well. The challenge lies in developing the technology to deliver the energy without degrading the environment. Renewable resources are available worldwide in quantities that dwarf current worldwide energy consumption by humans. Renewables also have the strong advantage that they do not create a waste stream of either CO_2 from fossil fuels or high-level radioactive waste, which are disadvantages of fossil and nuclear energy. However, resources for certain types of nuclear energy are available in such large quantities as to be almost limitless. Fossil fuels are available in amounts that could last for two or three centuries as well, if they can be extracted safely and combusted without emitting CO_2 to the atmosphere.

1-4-4 Discussion: Contrasting Mainstream and Deep Ecologic Perspectives on Energy Requirements

Underlying the previous discussion of addressing world poverty and global CO_2 emissions is a fundamental premise, namely, that increased access to energy per capita is a requirement for wealth, and that increased wealth will lead to improvements in human well-being. Based on earlier figures (Fig. 1-2 for GDP or Fig. 1-3 for HDI), the correlation between energy consumption and economic indicators support the idea that, as poor countries increase their access to energy, their position will rise along the wealth or HDI curve. Success in the area of wealth or HDI, it is reasonable to assume, will in turn lead to success in providing quality of life. By this logic, the wealthy countries of the world should not reduce their per capita energy consumption, since this would imply a loss of quality of life. Instead, these countries should make the inputs and outputs of energy systems environmentally benign. As long as this is done, the environment is protected at whatever level of energy consumption emerges, and the mix of activities in which their citizens engage (manufacturing, commerce, retailing, tourism, mass media entertainment, and the like) is no longer a concern. The technologies and systems thus developed can be made available to the emerging countries so that they too can have greater access to energy consumption and achieve a high quality of life in a sustainable way.

This "mainstream" perspective has been widely adopted by economists, engineers, and political leaders, but it is not the only one. Another approach is to fundamentally rethink the activities in which humans engage. Instead of allowing the mix of activities to continue in its present form, activities and lifestyles are chosen to reduce energy and raw material requirements as well as waste outputs, so that the effect on the environment is reduced to a sustainable level. This approach is one of the fundamental tools of *deep ecology*, an alternative philosophy for society's relationship with the natural world that has emerged in recent decades

By implication, deep ecology criticizes the mainstream approach of being one of "shallow ecology," which only addresses the surface of the ecological crisis by making technical changes to resource extraction and by-product disposal, and does not address the core problem of excessive interference in the natural systems of the world. For example, in the case of energy systems, instead of extracting energy resources or generating energy at the same rate but in a more environmentally friendly way, the deep ecologist seeks to change people's choices of end uses of energy so that much less energy is required. A primary target of this effort is *consumer culture*, that is, the purchase, especially by middle- and upper-class citizens of goods and services that are beyond what is necessary for basic existence, but that are thought to improve quality of life. Deep ecologists seek to reorient purchases and consumption away from consumer culture toward focusing on *essential* goods and services. In the long term, many among this group also advocate gradually reducing the total human population so as to reduce resource consumption and pollution.

The difference between the mainstream and deep ecologic approach can be illustrated using different countries' energy consumption per capita values, and considering how they might change in the future in each case. For instance, the country of Bangladesh is on the low end of the energy per capita spectrum, with a value of 6.8 GJ/person (6.4 million BTU/person). Zimbabwe was presented earlier as another country with low per-capita energy use, at 14.3 GJ/person. From Table 1-1, the equivalent value

agree that the low value of energy per capita limits the human potential of Bangladesh, since it implies difficulty in delivering adequate food, medical care, or other basic necessities. However, they diverge on what should be the *correct* target for energy intensity. In the mainstream approach, there is no restriction on Bangladesh eventually rising to the level of energy intensity of the United States, so long as the requirement for protecting the environment is met. By contrast, the deep ecologic approach envisions both countries aspiring to some intermediate value, perhaps on the order of 50 to 100 GJ/person (50 to 100 million BTU/person), due to improved access to environmentally friendly energy sources in Bangladesh and changes in lifestyle choices in the United States. In practical terms, both mainstream and deep ecologic approaches would approve of the development in Bangladesh of basic health care, adequate access to food to avoid hunger and starvation, and universal primary education—all of which are unmet needs at present. However, the mainstream approach would in addition encourage the development of universal access to mechanized transportation and widespread automobile ownership, a comprehensive network of power plants and electric grid, shopping malls and other commercial amenities, and so on, whereas deep ecology would oppose them.

The deep ecologic alternative not only incorporates some attractive advantages but also some significant challenges. The reduction of energy and resource consumption obtained by following the deep ecologic path can yield real ecological benefits. With less consumption of energy services, the rate of coal or oil being mined, renewable energy systems being produced and installed, CO_2 being emitted to the atmosphere, and so on, is reduced. In turn, reducing the throughput of energy, from resource extraction to conversion to the management of the resulting by-products, can simplify the challenge of reconciling energy systems with the environment. This problem is made more difficult in the mainstream case, where the throughput rate is higher.

However, in the short to medium term, the deep ecologic approach would challenge society because many of the activities in a modern service economy that appear not to be essential from a deep ecologic perspective are nevertheless vital to the economic well-being of individuals who earn their living by providing them. If demand for these services disappeared suddenly, it might reduce energy consumption and emissions but also create economic hardship for many people. Therefore, the adoption of a deep ecologic approach to solving the energy problem would require a transformation of the way in which economies in wealthy countries provide work for their citizens, which could only be carried out over a period measured in years or decades.

The number of persons fully committed to a deep ecologic path is relatively small at the present time, especially compared to the numbers adhering to the more mainstream idea of continued high levels of economic activity reconciled with adequate environmental safeguards. However, a related approach to personal behavior of giving environmental considerations priority in lifestyle and consumption decisions has started to influence the choices of some individual consumers. Understanding the environmental impact of choices concerning size of home, consumer purchases, travel decisions, and other available options, these consumers choose to forgo purchases that are economically available to them, so as to reduce their personal environmental footprint. This shift has in turn led to some curbing of growth in energy consumption in the industrialized countries among certain segments of society, for example, those who identify themselves as "environmentalists." It is likely that its influence will grow in the future, as will its impact on energy demand.

1-5 Energy Issues and the Contents of This Book

1-5-1 Motivations, Techniques, and Applications

The contents of this book can be divided into three parts: *motivations and drivers* (a part of which is provided by the preceding discussion in this chapter), *tools*, and *applications*. The flowchart in Fig. 1-12 graphically represents the logical connection between different parts of the book.

Three major challenges make up the *motivations and drivers* for the contents of the book, and are covered in the first five chapters. The first is "sustainable development" (covered in Chaps. 1 and 2), meaning continued development that meets human needs, especially in the emerging countries so that they may rise out of poverty, without irreversibly damaging the natural environment. Chief among the environmental concerns is climate change (Chap. 4), which requires that society stabilize (and possibly some day reduce) the amount of CO_2 in the atmosphere, through decisions about energy systems, among other things. Lastly, as the world continues to consume its supply of nonrenewable fossil fuels, oil and gas production will peak sometime in the next several decades, requiring the development of alternative energy sources, such as nonconventional fossil fuels with no CO_2 emissions to the atmosphere, or nonfossil fuels (Chap. 5).

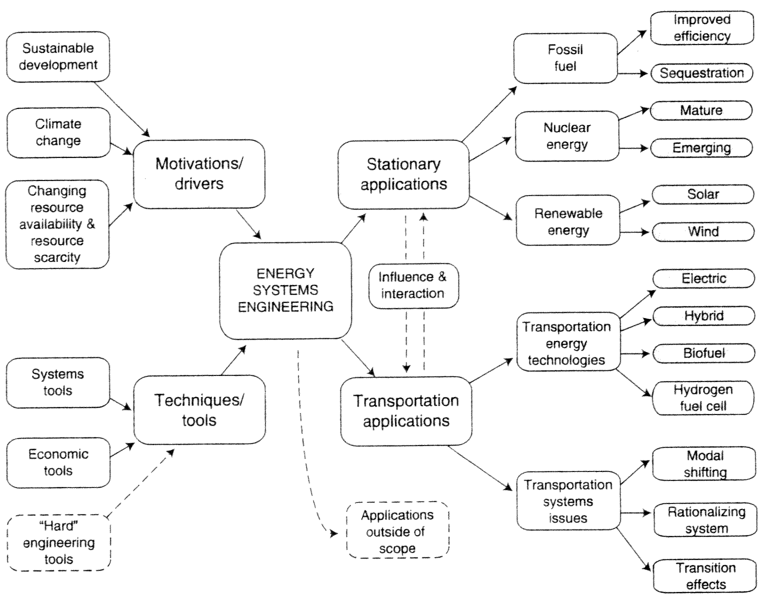


FIGURE 1-12 Flowchart of contents of book, including motivations/drivers, techniques/tools, and

At the lower left in the figure are "techniques and tools." First among these are the "hard" engineering tools, shown with a dashed line to indicate that they are the assumed background that the energy engineer brings to the study of energy systems—thermodynamics, heat transfer, fluid mechanics, electricity and magnetism, chemistry, and statistics. Techniques included in the book appear in Chaps. 2 and 3, including systems tools (Chap. 2), which are presented to help with the modeling of energy use as taking place in a system with interacting parts. These systems have a "life cycle" with distinct stages (planning, implementation, end use or operational lifetime, and dismantling/disposal), where each stage contributes to the overall success or failure of the system. Economic tools (Chap. 3) are also included, and these make the connection between energy systems as technologies and as financial investments, which include both upfront capital costs and ongoing maintenance and operating costs that must be repaid over time through revenues (energy sales, financial benefit of energy savings, and so on).

The motivations/drivers and tools/techniques feed directly in to the engineering of energy systems, that is, the applications covered in the remainder of the book. These are divided between stationary applications, represented by the generation of electricity and space or process heat; and transportation applications, covering all types of movement of vehicles by land, sea, or air. Linkages of "interaction and influence" connect the two application areas in several ways; for instance, the primary energy resources which they consume overlap in some areas, and there are synergies whereby demand in both areas can sometimes be met simultaneously. These two areas do not cover 100% of all energy end uses, so applications outside the scope of the book—representing no more than 10 to 15% of all end-use energy consumption—are shown with a dashed line.[11]

The stationary applications side is represented by the major conversion technologies covered in the book, with the assumption that the electricity and/or heat generated is then used for whatever purpose the end-user desires: indoor climate control, lighting, operations of appliances, and so on (the end uses themselves are largely outside the scope of the book). The stationary applications are divided among fossil fuel systems (Chaps. 6 and 7), nuclear energy systems (Chap. 8), and renewable energy systems (Chaps. 9–14). Transportation applications are divided between the individual vehicle propulsion technologies (Chap. 15), and the systems issues that arise when the propulsion systems are manifested, in the form of a great number of vehicles, vessels, and aircraft, in the world's multimodal transportation network (roads, railroads, waterways, air networks, and pipelines, as discussed in Chap. 16). Chapter 17 briefly discusses some technologies not treated in greater depth in the body of the book, along with providing conclusions regarding future prospects for energy.

1-5-2 Initial Comparison of Three Underlying Primary Energy Sources

While the number of possible applications in Fig. 1-12 is large, the primary energy sources that underlie them consist of just three: fossil, nuclear, and renewable. Since the fundamental characteristics of each of these primary sources has a strong impact on how each is subsequently converted, transmitted, and used, it is useful in this introductory chapter to (1) make some basic comparisons before delving into greater depth in

[11]For example, some fraction of the total fossil fuels extracted annually is used as feedstocks for the

Chaps. 6 to 16, and (2) to present a possible pathway for how the mix of primary energy might evolve in the twenty-first century in response to the motivations and drivers discussed above. The remainder of this section focuses on these two objectives.

Table 1-2 presents some basic advantages and disadvantages of the three types of primary energy. *Fossil energy* includes any carbon- or hydrocarbon-based resource extracted from subsurface resources and provides approximately 82% of world energy at present (using 2012 figures), down from 85% in the year 2000. Although convenient due to their universal familiarity and relatively low direct cost (i.e., not including the cost of pollution or accidents), fossil fuels are relatively finite in supply compared to their current rate of global consumption, and are the leading contributor to the increase in concentration of CO_2 in the atmosphere. *Nuclear energy* includes all types of primary energy derived from nuclear bonds as opposed to chemical bonds in the case of fossil fuels. Nuclear energy emits no greenhouse gases or other air pollution during production at a nuclear power plant, but carries risks from radiation in case of nuclear plant accidents and from the accumulation of long-lived, highly radioactive wastes that result from the use of nuclear fuel. *Renewable energy* comprises any systems that convert reoccurring energy fluxes in nature, many of them originating from the incidence of solar energy on the Earth, into a form of energy that can be used in human-built systems. Renewable energy is vast in its total global availability in nature and causes no greenhouse gas emissions or pollution in its conversion and end use.

Turning to the second objective, it is useful not only to evaluate the three primary sources of energy today, but also to consider how they might be used in the future to achieve a sustainable global energy solution for the twenty-first century. At present

	Advantages	**Disadvantages**
Fossil	The dominant primary energy source at present (85% of world demand). Relatively low capital cost. Often has relatively low direct total cost including fuel cost. "Dispatchable," i.e., user controls when fuel is converted (to electricity, mechanical motion, etc.).	Fuel cost can be volatile. Emits CO_2 to atmosphere, unless otherwise controlled. Extraction can be destructive. Risk of accidents during extraction. Limits on ultimately recoverable supply.
Nuclear	Relatively low fuel cost, and fuel cost not volatile. Emits no CO_2 or other air pollutants during generation. Dispatchable. Ultimately recoverable fuel supply potentially much larger than fossil fuel supply.	High capital cost of construction. Risk of radiation in case of accidents. Need for long-term storage of highly radioactive, long-lived waste products.
Renewable	"Fuel" does not cost anything in many cases (wind, sun). Energy supply is inexhaustible. Total energy supply based on total sunlight intercepted by Earth is very large. Emits no CO_2 or other air pollutants during generation.	High capital cost of construction. Intermittent rather than dispatchable nature for many renewable sources. Energy supply in nature is often diffuse, requiring large area as well as large amount of capital equipment.

TABLE 1-2 Basic Advantages and Disadvantages of Three Types of Primary Energy: Fossil,

nuclear energy contributes about 7% of global primary energy, and renewable energy about 11%, with fossil energy supplying the rest. We begin with two assumptions related to population and per capita energy consumption:

1. Global population growth will slow and reach a plateau of around 9 billion people around the year 2060, and will remain approximately constant at that level from 2060 to 2100. This scenario is based on a United Nations midrange projection of the path of population growth in the twenty-first century.
2. Average global per capita energy consumption will rise for the rest of the century due to gradually rising values in industrializing countries such as China, India, or Brazil, and also falling values in wealthy countries, so that the average across all countries stabilizes at 100 million BTU/person by the end of the century.

In addition, it is assumed that to create a representative outcome, each of the three primary sources will contribute one-third of the energy supply at the end of the century. Since conventional fossil (i.e., fossil combustion with uncontrolled release of CO_2 to the atmosphere) is incompatible with protecting the climate, carbon capture with sequestration (CCS), will displace conventional fossil so that eventually, all remaining fossil energy use will emit no CO_2.

The results, which displace the 85% conventional fossil used in 2000 with a mix of noncarbon emitting sources by 2100, are shown in Fig. 1-13. The mix, comprising a contribution of a third each, from fossil, nuclear, and renewable was chosen arbitrarily, so no inferences regarding the relative strength or weakness of different sources should be derived from it. Nevertheless, if this situation were achieved, since both per capita energy use and population would stabilize by 2100, the world might continue to meet the global need for energy for some time thereafter, using the mix of resources shown. Eventually, the one-third portion contributed by CCS would need to be replaced by some mix of the other two sources, as fossil resources decline in availability and are

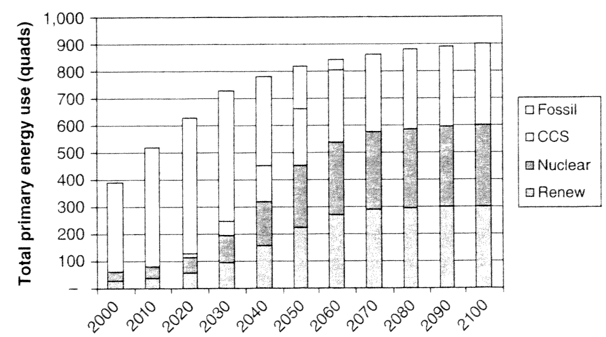


FIGURE 1-13 A possible pathway for primary energy production in the twenty-first century arriving at 100 million BTU/person, on average, available for 9 billion people in 2100.
Note: "Fossil" = fossil energy without sequestration, "CCS" = fossil energy with carbon capture

ultimately exhausted. Indeed, if the actually recoverable amount of fossil resource cannot sustain the production for the twenty-first century shown for Fossil/CCS in Fig. 1-13, then the substitution of some combination of nuclear and renewable for CCS would need to happen sooner than the year 2100.

Two other comments are in order regarding the rate of transition from fossil to CCS. First, rate of substitution of CCS for fossil is chosen to approximately achieve the commonly stated goal of reducing CO_2 emissions by 80% in the industrialized countries and by some lesser amount in the emerging countries by the year 2050. Thereafter fossil drops to less than 5% in 2060 and disappears by 2070. Nevertheless, even though the goal of 100% CO_2-emission-free energy is achieved by 2070, there is still a large increase in total fossil (i.e., non-CCS) energy use between 2000 and 2020, and only thereafter does fossil energy use gradually decline. Second, this path is in line with currently observed rapid growth in global fossil energy use, but it may not arrive quickly enough for the community of nations to effectively counteract climate change, the impacts of which are growing increasingly severe. If stronger measures were taken than are currently in place, the phase-out of conventional fossil might take place more rapidly than what is shown in the figure.

A more detailed consideration of the strengths and weaknesses of the three types of energy and possible pathways to energy sustainability are included in the conclusions in Chap. 17. The intervening Chaps. 2 to 16 provide the content to support a more sophisticated treatment at the end of the book.

1-6 Units of Measure Used in Energy Systems

Many units of measure used in energy systems are already familiar to readers, and some, namely the watt, joule, and BTU, and multiples thereof such as the GJ or EJ, have been used in the preceding sections. Units in common use throughout this book are defined here, while some units unique to specific technologies are defined later in the book where they arise. It is assumed that the reader already understands basic metric units such as the meter, gram, seconds, and degrees Celsius.

1-6-1 Metric (SI) Units

The system of measure in use in most parts of the world is the *metric* system, which is sometimes also referred to as the SI system (an abbreviation for International System). For many quantities related to energy, the United States does not use the metric system; however, the unit for electricity in the United States, namely, the watt, is an SI unit.

The basic unit of force in the metric system is the *newton* (N). One newton of force is sufficient to accelerate the motion of a mass of 1 kg by 1 m/s in 1 s, that is

$$1\ \text{N} = 1\ \text{kg} \cdot \text{m/s}^2 \qquad (1\text{-}5)$$

The basic unit of energy in the metric system is the *joule* (J), which is equivalent to the exertion of 1 N of force over a distance of 1 m. Thus

$$1\ \text{J} = 1\ \text{N} \cdot \text{m} \qquad (1\text{-}6)$$

The basic unit of power, or flow of energy per unit of time, is the *watt*, which is equivalent to the flow of 1 J of energy per second. Therefore

A convenient alternative measure of energy is the flow of 1 W for an hour, which is denoted 1 *watthour* (Wh). A commonly used measure of electrical energy is the *kilowatthour*, which is abbreviated kWh and consists of 1000 Wh. Since both joules and watthours are units of energy, it is helpful to be able to convert easily between the two. The conversion from watthours to joules is calculated as follows:

$$(1\ \text{Wh})\left(3600\frac{\text{s}}{\text{h}}\right)\left(\frac{1\ \text{J/s}}{\text{W}}\right) = 3600\ \text{J} \qquad (1\text{-}8)$$

In other words, to convert watthours to joules, multiply by 3600, and to convert joules to watthours, divide by 3600.

The quantity of energy in an electrical current is a function of the current flowing, measured in *amperes* (A), and the change in potential, measured in *volts* (V). The transmission of 1 W of electricity is equivalent to 1 A of current flowing over a change in potential of 1 V, so

$$1\ \text{W} = 1\ \text{VA} \qquad (1\text{-}9)$$

The unit *voltampere* (VA) may be used in place of watts to measure electrical power.

Metric units are adapted to specific applications by adding a prefix that denotes a multiple of 10 to be applied to the base unit in question. Table 1-3 gives the names of the prefixes from micro- (10^{-6}) to exa- (10^{18}), along with abbreviations, numerical factors, and representative uses of each prefix in energy applications. A familiarity with the practical meaning of each order of magnitude can help the practitioner to avoid errors in calculation stemming from incorrect manipulation of scientific notation. For instance, the annual output of a coal- or gas-fired power plant rated at 500 MW should be on the order of hundreds or thousands of GWh, and not hundreds or thousands of MWh.

Prefix	Symbol	Factor	Example
Micro-	μ	10^{-6}	Microns (used in place of "micrometers") ~ wavelength of visible light
Milli-	m	10^{-3}	Milliampere ~ current flow from a single photovoltaic cell
Kilo-	k	10^{3}	Kilowatthour ~ unit of sale of electricity to a residential customer
Mega-	M	10^{6}	Megawatt ~ maximum power output of the largest commercial wind turbines
Giga-	G	10^{9}	Gigawatthour ~ measure of the annual output from a typical fossil-fuel-powered electric power plant
Tera-	T	10^{12}	Terawatt ~ measure of the total rated capacity of all power plants in the world
Peta-	P	10^{15}	Petajoule ~ measure of all the energy used by the railroads in the United States in 1 year
Exa-	E	10^{18}	Exajoule ~ measure of all the energy used by an entire country in 1 year

Table 1-3 Prefixes Used with Metric Units

Large amounts of mass are measured in the metric system using the *metric ton*, which equals 1000 kg; hereafter it is referred to as a *tonne* in order to distinguish it from U.S. customary units. The tonne is usually used for orders of magnitude above 10^6 g and units based on the tonne such as the kilotonne (1000 tonnes, or 10^9 g), megatonne (10^6 tonnes), and gigatonne (10^9 tonnes) are in use. The abbreviation "MMT" is used to represent units of million metric tonnes.

As an example of conversion between units involving metric units that have prefixes, consider the common conversion of kWh of energy to MJ, and vice versa. The conversion in Eq. (1-6) can be adapted as follows:

$$(1\ \text{kWh})\left(3600\ \frac{\text{s}}{\text{h}}\right)\left(1000\ \frac{\text{W}}{\text{kW}}\right)\left(1\ \frac{\text{J/s}}{\text{W}}\right)\left(\frac{1\ \text{MJ}}{1\times10^6\ \text{J}}\right)=3.6\ \text{MJ} \tag{1-10}$$

In other words, to convert kWh to MJ, multiply by 3.6, and to convert MJ to kWh, divide by 3.6.

Example 1-1 A portable electric generator that is powered by diesel fuel produces 7 kWh of electricity during a single period of operation. (a) What is the equivalent amount of energy measured in MJ? (b) Suppose the fuel consumed had an energy content of 110 MJ. If the device were 100% efficient, how much electricity would it produce?

Solution

(a) 7 kWh × 3.6 MJ/kWh = 25.2 MJ

(b) 110 MJ/3.6 MJ/kWh = 30.6 kWh

1-6-2 U.S. Standard Customary Units

The basic units of the U.S. customary units (sometimes referred to as *standard* units) are the pound mass (lbm) or ton for mass; the pound force (lbf) for force; the degree Fahrenheit (F) for temperature; and inch (in), foot (ft), or mile (mi) for distance. One pound is equivalent to 0.454 kg. One standard ton, also known as a *short ton*, is equal to 2000 lb and is equivalent to 907.2 kg or 0.9072 tonne. One pound force is equivalent to 4.448 N. A change in temperature of 1°F is equivalent to a change of 0.556°C.

The most common unit of energy is the *British thermal unit*, or BTU. One BTU is defined as sufficient energy to raise the temperature of 1 lbm of water by 1°F at a starting temperature of 39.1°F, and is equivalent to 1055 J. At other starting temperatures, the amount of heat required varies slightly from 1 BTU, but this discrepancy is small and is ignored in this book. A unit of 1 quadrillion BTU (10^{15} BTU) is called a *quad*. The units BTU/second (equivalent to 1.055 kW) and BTU/hour (equivalent to 3.798 MW) can be used to measure power. Typical quantities associated with increasing orders of magnitude of BTU measurements are given in Table 1-4.

Number of BTUs	Typical Measurement
Thousand BTUs	Output from portable space heater in 1 h
Million BTUs	Annual per capita energy consumption of various countries
Billion BTUs	Annual energy consumption of an office park in the United States
Trillion BTUs	Total annual energy consumption of all railroads in the United States or European Union from train and locomotive movements
Quadrillion BTUs (quads)	Annual energy consumption of an entire country

An alternative unit for power to the BTU/hour or BTU/second is the horsepower, which was developed in the late 1700s by James Watt and others as an approximate measure of the power of a horse. The inventors of the unit recognized that no two horses would have exactly the same output, but that a typical horse might be able to raise the equivalent of 33,000 lb by 1 ft of height in the time interval of 1 min, which is equivalent to 746 W.

In the United States, the unit used to measure the average efficiency of electric power production is a hybrid standard-metric unit known as the *heat rate*, which is the average amount of heat supplied in thermal power plants, in BTUs, needed to provide 1 kWh of electricity. For example, a heat rate of 3412 BTU/kWh is equivalent to 100% efficiency, and a more realistic efficiency of 32% would result in a heat rate of 10,663 BTU/kWh.

1-6-3 Units Related to Oil Production and Consumption

In some cases, the energy content of crude oil is used as a basis for making energy comparisons. A common measure of oil is a *barrel*, which is defined as 42 U.S. gallons of oil, or approximately the volume of a barrel container used to transport oil. (Note that the U.S. gallon is different from the *imperial gallon* used in Britain, one imperial gallon containing approximately 1.2 U.S. gallons.) A unit in common use for measuring the energy content of large quantities of energy resources is the *tonne of oil equivalent*, abbreviated "toe," which is the typical energy content of a tonne of oil. One barrel of oil has 0.136 toe of energy content, and one toe is equivalent to 42.6 GJ of energy. National and international energy statistics are sometimes reported in units of toe, ktoe (1000 toe), or mtoe (million toe), in lieu of joules; the International Energy Agency, for example, reports the energy balances of member countries in ktoe on its Website.

1-7 Summary

Modern energy supplies, whether in the form of electricity from the grid or petroleum-based fuels for road vehicles, have a profound influence on human society, not only in the industrialized countries but also in the industrializing and less developed countries. While humanity began to develop these systems at the dawn of recorded history, their evolution has greatly accelerated since the advent of the industrial revolution around the year 1800. Today, energy use in the various countries of the world is highly correlated with both the GDP and HDI value for that country, and as countries grow wealthier, they tend to consume more total energy and energy per capita. This situation creates a twin challenge for the community of nations, first of all to provide sufficient energy to meet growing demand and second, to reduce the emission of CO_2 to the atmosphere. There are two systems for measuring quantities of energy in use in the world, namely, the metric system, used by most countries, and the U.S. customary system used in the United States; some common units are joules or BTUs for energy or watts for power.

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Exercises

1-1. Use the Internet or other resources to chart the development of an energy technology, from its earliest beginnings to the present day. Did the roots of this technology first emerge prior to the start of the industrial revolution? If so, how? If not, when did the technology first emerge? In what ways did the industrial revolution accelerate the growth of the technology? More recently, what has been the impact of the information age (e.g., computers, software, electronically controlled operation, and the Internet, and the like) on the technology?

1-2. For a country of your choice, obtain time series data for total energy consumption, CO_2 emissions, population, and GDP and/or HDI. If possible, obtain data from 1980 to the most recent year available, or if not, obtain some subset of these yearly values. These data can be obtained from the U.S. Energy Information Agency (www.eia.gov), the International Energy Agency (www.iea.org), or other source. Compare the trend for this country for measures such as energy use per capita and GDP earned per unit of energy to that of the United States or China.

1-3. The country of Fictionland has a population of 31 million and consumes on average 12.09 exajoule (EJ), or 11.46 quads, of energy per year. The life expectancy of Fictionland is 63 years, and the GDP per capita, on a PPP basis, is $13,800. The adult literacy rate is 75%. The eligible and actual student enrollments for primary, secondary, and college/university levels of education are given in the table below:

	Eligible	Enrolled
Primary	2,500,000	2,375,000
Secondary	2,100,000	1,953,000
University	1,470,000	558,600

a. Calculate the HDI for Fictionland.

b. How does Fictionland's HDI to energy intensity ratio compare to that of the countries in the scatter charts in the chapter? Is it above, below, or on a par with these other countries?

1-4. Regression analysis of population, economic, and environmental data for countries of the world. For this exercise, download from the Internet or other data source values for the population, GDP in either unadjusted or PPP form, energy consumption, and land surface area of as many countries as you can find. Then answer the following questions:

a. From the raw data you have gathered, create a table of the countries along with their GDP per capita, energy use per capita, and population density in persons per square kilometer or square mile.

b. In part (a), did your data source allow you to include figures for all three measures for all the major countries of all the continents of the world? If not, what types of countries was it not possible to include, and why do you suppose this might be the case?

c. Using a spreadsheet or some other appropriate software, carry out a linear regression analysis of energy consumption per capita as a function of GDP per capita. Produce a scatter chart of the values and report the R^2 value for the analysis.

d. One could also speculate that population density will influence energy consumption, since a densely populated country will require less energy to move people and goods to where they are needed. Carry out a second regression analysis of energy consumption per capita as a function of population density. Produce a scatter chart of the values and report the R^2 value for the analysis.

e. Discussion: Based on the R^2 value from parts (c) and (d), how well do GDPpc and population density predict energy consumption? What other independent variables might improve the model? Briefly explain.

f. Given the global nature of the world economy, what are some possible flaws in using energy consumption figures broken down by country to make statements about the relative energy consumption per capita of different countries?

1-5. According to the U.S. Department of Energy, in 2005 the United States' industrial, transportation, commercial, and residential sectors consumed 32.1, 28.0, 17.9, and 21.8 quads of energy, respectively. What are the equivalent amounts in EJ?

1-6. From Fig. 1-8, the energy consumption values in 2000 for the United States, Japan, China, and India are 104, 23.7, 40.9, and 14.3 EJ, respectively. What are these same values converted