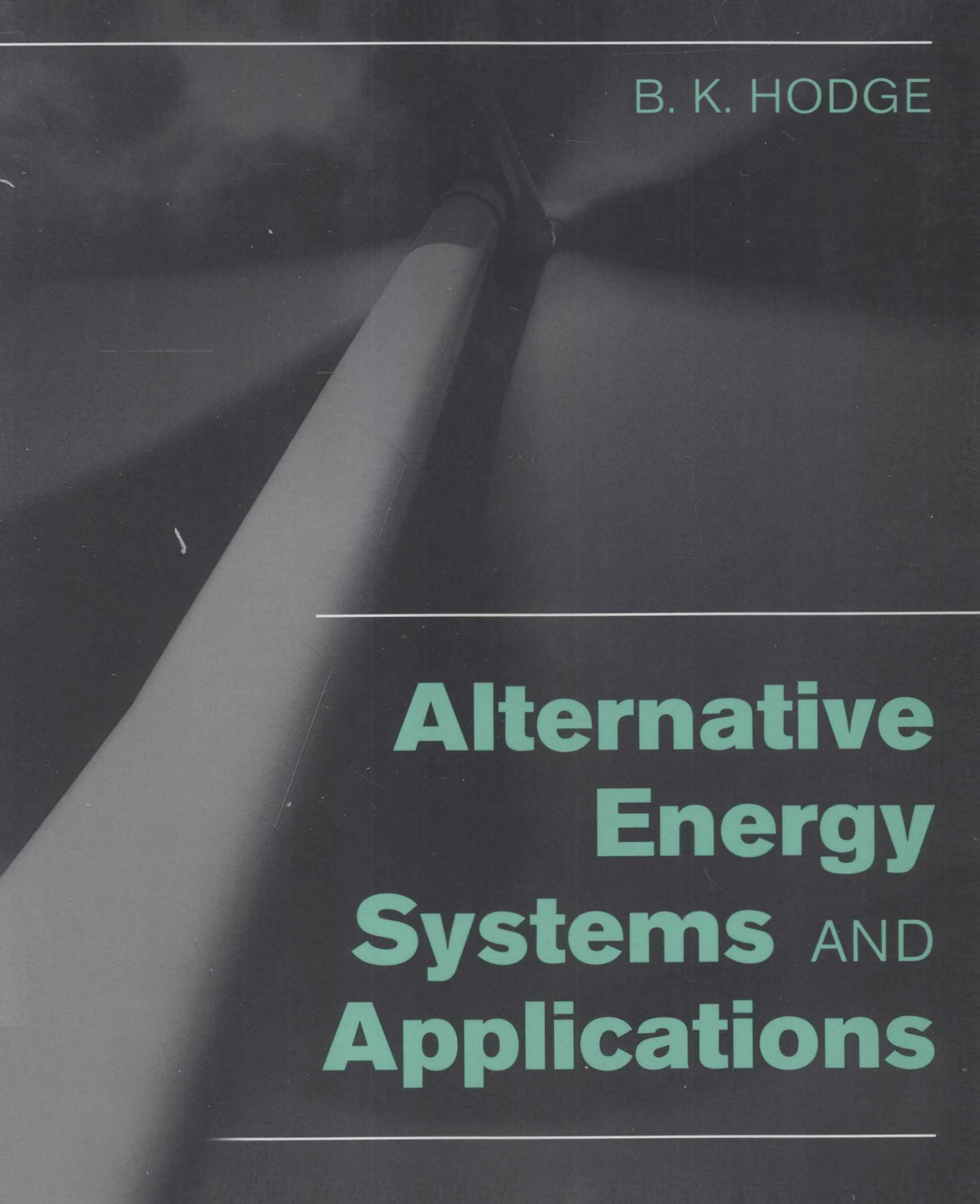

B. K. HODGE

Alternative Energy Systems AND Applications

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B. K. Hodge

Mississippi State University

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Alternative Energy Systems and Applications

To Gayle, my wife
and best friend

Preface

In recent years much has been made of the impact of the myriad energy problems faced not only by the United States, but also the rest of the world. These impacts range from energy security issues (the dependence on imported energy sources) to economic issues (gasoline reached $4.00/gallon in the summer of 2008) to energy sustainability issues (minimum environmental and ecological impacts). Many in the engineering, corporate, and political communities advocate greater reliance on alternative energy sources. Because of the increased interests in such topics, a number of books on subjects ranging from sustainable energy to renewable energy to alternative energy have been offered in recent years. However, many of these books contain mostly qualitative information with little in the way of quantitative information or "engineering" calculations or procedures. Some also advocate specific alternative energy scenarios and some do not present balanced discussions. This textbook was written to address the above concerns.

Alternative Energy Systems and Applications is suitable for use at the senior or beginning graduate level for students in mechanical engineering or in energy-engineering related fields. Familiarity with the basic concepts of fluid mechanics, thermodynamics, and heat transfer is presumed in the development of the topics in the book, but maturity in these subjects is not needed in order to understand the developments.

The title, *Alternative Energy Systems and Applications*, is used to convey the idea that the topics covered encompass both alternative energy sources and alternative uses of existing energy sources. The solution to the current energy dilemma will contain features of both. The breadth of topics proposed for the book is delineated in the chapter headings. Chapter 1 critically examines energy usage in the United States. Although not explicitly subdivided into congruent topical areas, Chapters 2–5 treat turbomachine-based topics (hydro, wind, and combustion turbines), Chapters 6–9 consider solar-based topics (active, passive, and photovoltaic), Chapters 10–11 examine fuel cells and CHP (combined heating and power) applications, and Chapters 12–15 complete the review of alternative energy concepts (biomass, geothermal, ocean, and nuclear).

All chapters except chapter 1 broadly fit into one of two categories—(1) a review of the background information necessary for a topic or (2) an exploration of an alternative energy source or an alternative use of an existing energy source. Chapters 2 and 6, for example, are used to review the backgrounds necessary for turbomachines and solar energy, respectively.

Often alternative energy topics are equated to renewable energy resource discussions. In this book, Chapters 3–4, 7–9, and 12–14 consider topics usually associated with renewable energy resources. The chapters dealing with renewable energy topics present the physical principles involved in harvesting the renewable, review (in most cases) the amount of the renewable resource available, examine quantitative aspects of the harvesting, point out difficulties with utilizing the renewable resource, discuss limitations and economics aspects, and provide, if applicable, examples of commercial systems for harvesting the renewable. Where appropriate, website addresses are cited.

The chapters addressing alternative uses of existing energy sources are focused on applications. Combustion turbines, fuel cells, and CHP systems represent alternative uses of existing energy sources. The application chapters basically discuss the operation, the thermodynamic aspects, and the expected efficiencies of such systems and provide examples. As with the renewable energy topics, suitable websites are referenced.

All chapters, except Chapter 1, contain worked examples and review questions and exercise problems. The focus is on first-order engineering calculations. Mathcad® is used as the computational software system throughout the book. However, the examples/problems are fundamental, and many other computational systems (MATLAB®, EES, Mathematica®) could be readily adopted for use with little effort. The intent of the book is to provide students with a quantitative approach to alternative energy sources and alternate applications of existing energy sources. Since this is a survey textbook, it does not attempt to provide detailed engineering information on the topics discussed, but references are provided that do contain detailed engineering information.

This textbook is the outgrowth of several years of teaching ME 4353/6353 Alternate Energy Sources in the Bagley College of Engineering at Mississippi State University. The discretionary funds provided to me as holder of the Tennessee Valley Authority Professorship in Energy Systems and the Environment at Mississippi State University were very helpful in this endeavor and are acknowledged. Additionally, thanks are due to Professors Francis Kulacki, James Mathias, and David Ruzic who reviewed the manuscript. Their comments and insights were quite useful.

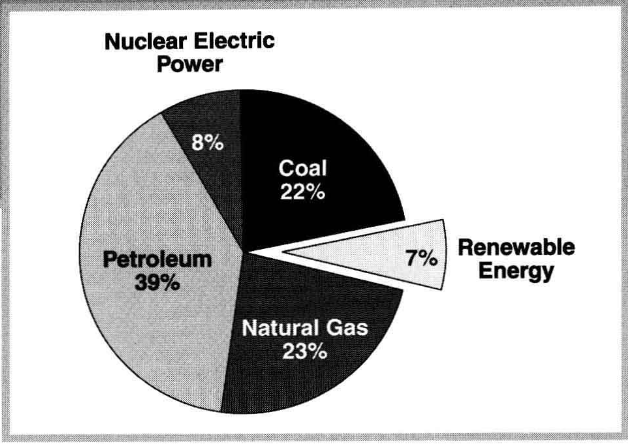
B. K. Hodge
Mississippi State University
January 2009

Contents

CHAPTER

1

Energy Usage in the United States



1.1 ENERGY AND POWER

A review of the customary units used for energy and power is appropriate to initiate a study of alternative energy sources and applications. Although much of the world uses the SI system (Système international d'unités), the United States, in addition to the SI system, uses the English Engineering and the British Gravitational systems of units. The unit of energy in the SI system is the N-m (newton-meter), which is also defined as the joule (J). Energy in the English Engineering (EE) system is defined as the Btu (British thermal unit), or alternatively, the ft-lbf (foot-pound force). Power is the rate of energy usage or transfer in J/sec, Btu/sec, or ft-lbf/sec. Power equal to 1 J/sec is defined as a watt (W). The most frequently used power unit is kilowatt (kW), or 1000 W. In the United States, power is sometimes expressed in terms of horsepower (hp), where 1 hp is 550 ft-lbf/sec or 0.7457 kW. The kilowatt-hour (kWh) is another frequently used unit of energy and represents a unit of energy (kW) multiplied by a unit of time (hour). The conversion is 3412.14 Btu = 1 kWh.

Tester et al. (2005) provide a sampling of power expenditures for various activities. Some of their results are reproduced as Table 1.1. The range of power expended is astonishing, about 9 orders of magnitude.

1.2 ENERGY USAGE AND STANDARD OF LIVING

An irrefutable fact is that the developed countries (the United States, Japan, the United Kingdom, etc.) use more energy per capita than the less developed countries (Mexico, Indonesia, etc.). Figure 1.1, taken from Tester et al. (2005), graphically presents energy consumption per capita as a function of gross national product (GNP) per capita for a number of countries. For the industrialized countries, the GNP per capita is from \$15,000 to \$25,000 while the energy consumption per capita is from

TABLE 1.1 Power expenditures for various activities

Activity	Power Expended
Pumping human heart	1.5 W = 1.5 × 10^{-3} kW
Household light bulb	100 W = 0.1 kW
Human, hard work	0.1 kW
Draft horse	1 kW
Portable floor heater	1.5 kW
Compact automobile	100 kW
SUV	160 kW
Combustion turbine	5000 kW = 5 MW
Large ocean liner	200,000 kW = 200 MW = 0.2 GW
Boeing 747 at cruise	250,000 kW = 250 MW = 0.25 GW
Coal-fired power plant	1 × 10^6 kW = 1000 MW = 1 GW
Niagara Falls hydroelectric plant	2 × 10^6 kW = 2000 MW = 2 GW

150 GJ to 325 GJ. The United States and Canada have the highest energy consumption per capita. A number of reasons exist for the high energy consumption per capita in the United States, among them (1) historically cheap energy, (2) low population density, (3) large area, and (4) a history of abundant domestic energy.

As discussed later in this chapter, low energy costs and domestic energy abundance are a thing of the past, and the United States faces escalating energy costs and

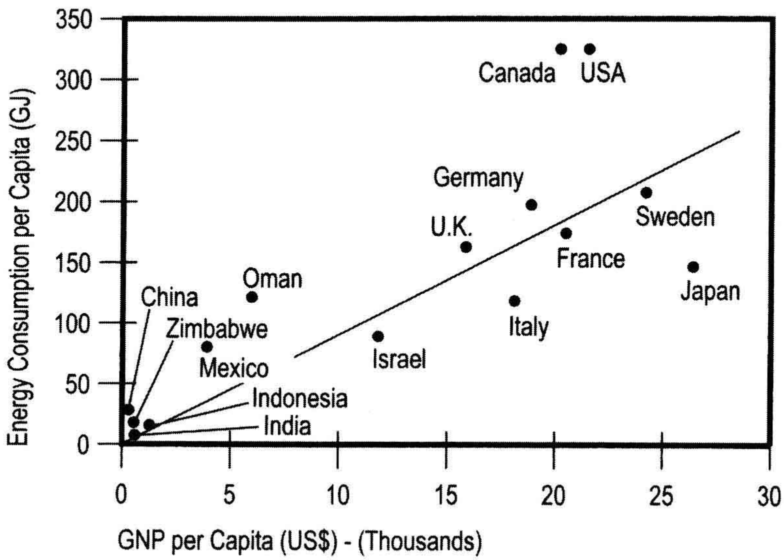


Figure 1.1 Per capita energy consumption versus gross national product (GNP) per capita for a number of countries (Tester et al. 2005).

the need for increasing energy imports (chiefly in the form of oil). The long-term implications of growing energy costs and imports will dramatically affect both the economy and the foreign policy posture of the United States. Indeed, the basis of this textbook is the need to consider both alternative energy sources and alternative (read more efficient) energy applications to address the energy problems facing the United States.

The energy problem in the United States is exacerbated by measures by other countries (India and China, for example) to increase the standard of living for their citizens. World energy consumption is rising faster than energy consumption in the United States.

1.3 A HISTORICAL PERSPECTIVE OF ENERGY USAGE IN THE UNITED STATES

The Energy Information Administration (EIA) of the United States Department of Energy (USDOE) provides a readily accessible and up-to-date source of energy statistics. The EIA website is www.eia.doe.gov. The EIA provides on a timely basis yearly energy statistics for the United States. These yearly energy summaries, titled *Annual Energy Review*, appear about eight months after the end of the calendar year and can be accessed at www.eia.doe.gov/aer. The information contained in this text is from calendar year 2007 and carries the USDOE accession number DOE/EIA-0384 (2007).

Figure 1.2, a mosaic of nighttime satellite photographs of the United States, is a rather dramatic illustration of the population density and dispersion and of the population of the United States, as well as the energy intensity distribution of night lighting (primarily from electricity usage).

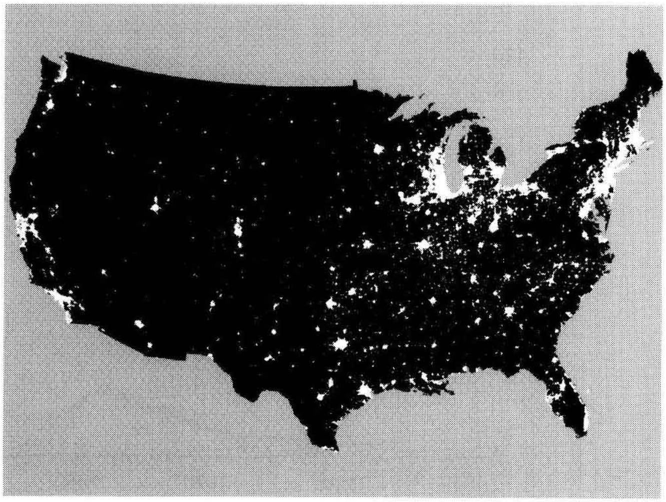


Figure 1.2 Mosaic of nighttime satellite photographs of the United States (EIA 2007).

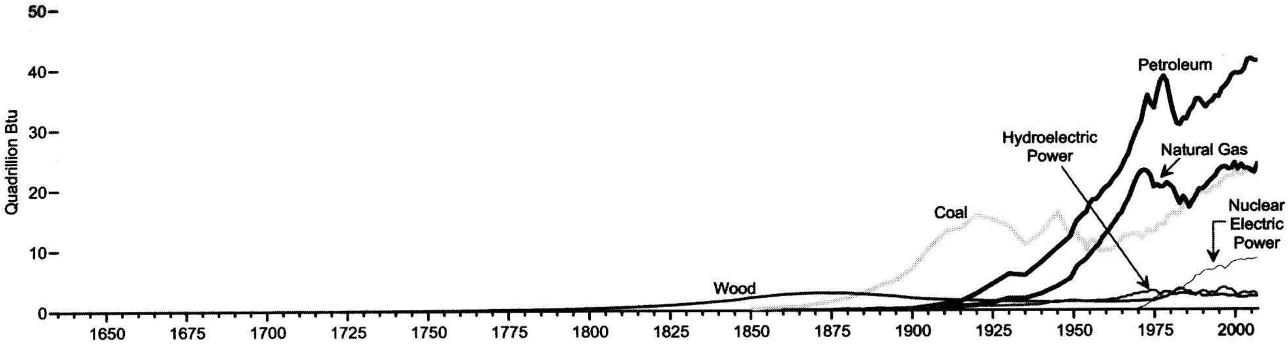


Figure 1.3 Historical energy utilization in the United States (EIA 2008).

Consider how the United States arrived at its current energy economy. Figure 1.3, taken from the EIA *Annual Energy Review 2007*, presents a graphical representation of historical energy utilization. The energy unit used is the quad (equal to 1 quadrillion Btu = 10^{15} Btu). Until the mid-1800s, energy utilization was mostly wood, with coal becoming increasingly important after 1850. By 1900 coal usage was much greater than wood usage, and petroleum was becoming more important as an energy source. In 1950 petroleum usage exceeded coal usage, and natural gas usage was dramatically rising. At the turn of the millennium, petroleum provided the most energy, with natural gas and coal vying for second and third place. Nuclear power was in fourth place, with hydroelectric and renewable energy (including wood) sources making the smallest contributions. In the next section, details of the energy utilization in 2007 will be explored.

The genesis of the energy problem is illustrated in Figure 1.4. Until about 1950, the United States had little dependence on energy imports. However, with the

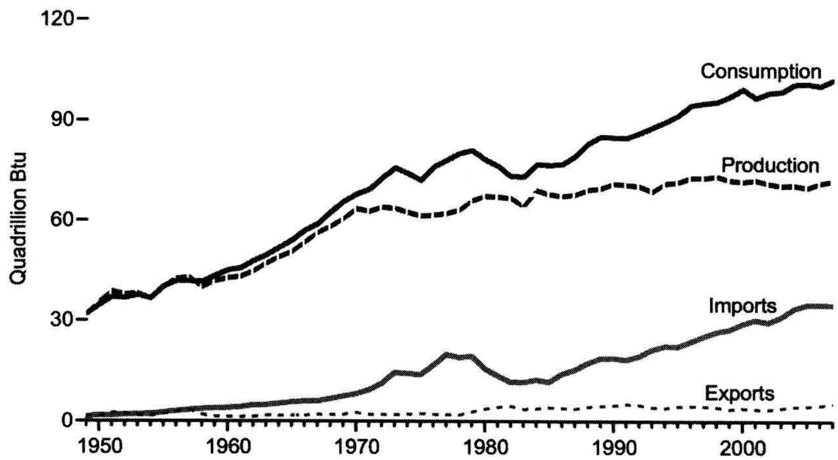


Figure 1.4 Energy consumption, imports, and exports for the United States.

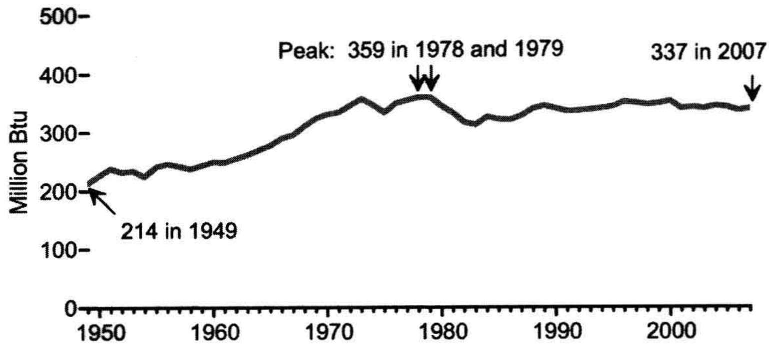


Figure 1.5 Historical per capita energy consumption in the United States.

post–World War II prosperity, energy exports began to increase as consumption outpaced domestic production. Since the 1980s, domestic production has increased, but at a rate slower than consumption has increased. The result has been a steady increase in energy imports.

Further explanation of how the United States arrived at its current rate of energy consumption is provided in Figures 1.5 and 1.6. Figure 1.5 tracks per capita energy consumption, and Figure 1.6 displays energy use per dollar of gross domestic product. Per capita energy consumption peaked at 360 million Btu in 1978 and declined during the "energy crisis" of the 1970s and 1980s. Some slight increases occurred during the 1990s, and in 2007 the per capita energy consumption was 337 million Btu. The energy crisis resulted in no dramatic decrease in per capita energy consumption in the United States; these results explain, in part, the current energy dilemma of the United States. In short, the United States failed to understand and heed the warnings of the first energy crisis. Figure 1.6 represents the energy usage per dollar of gross national product (GNP). Since the 1980s, the energy consumed per dollar of GNP has meaningfully declined from nearly 18,000 Btu to the 2007 value of 8,780 Btu. This decline is attributed to increased energy efficiency, especially in manufacturing, and to structural changes in the economy (the migration of much energy-intensive industry to other countries).

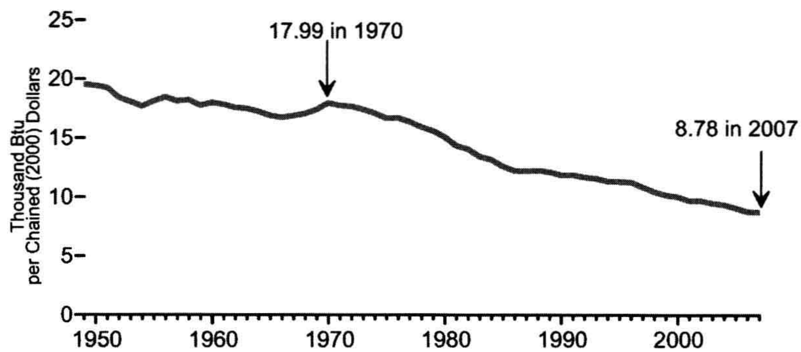


Figure 1.6 Historical energy use per dollar of gross domestic product in the United States.