ENERGY FOR SUSTAINABILITY

Technology, Planning, Policy

John Randolph and
Gilbert M. Masters

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Dedication

To Sandy and Mary, who are the sources of our inspiration,
and to our boys who inherit the world we leave them.

Contents

Preface

Energy has emerged as one of the most significant and pervasive issues society will face in the twenty-first century. Our 40 percent dependence on oil raises questions of national security and economic stability. Our 85 percent dependence on fossil fuels is generating carbon emissions that are causing global warming, perhaps the most severe environmental problem of the century. Our exploding global demand for energy s inequitable and exacerbates both oil and carbon problems.

This book is based on the premise that our current patterns of global and U.S. energy use are not sustainable. Further, it contends that, although a mix of energy sources will continue to be necessary, the security and sustainability of our energy use depend on significant improvements in efficiency of use and increased development of renewable energy systems. The book provides the rationale for this premise and presents the technical background, system design fundamentals, economic analysis, and planning and policy approaches to advance the transition to more sustainable patterns of energy production and consumption.

As a critical public, economic, environmental, and social issue, energy has become an interdisciplinary field, yet few citizens and government and industry leaders fully appreciate or have sufficient understanding of its many dimensions, challenges, and uncertainties. As a result, this book is interdisciplinary to provide the multidimensional perspectives and knowledge necessary to achieve sustainable energy. To cross disciplinary boundaries necessary for people to understand and implement energy solutions, we see two audiences for this book: the engineers and scientists (the "techies") who must develop the energy systems needed to transform our patterns of energy use; and the social scientists, planners, and policy makers (the "fuzzies") who must develop the social, economic, and political case necessary to adopt the policies and public attitudes needed to transform our patterns of energy use. To achieve sustainable energy, each of these groups must understand the other. We need to make the "techies" more fuzzy and the "fuzzies" more techy, and this book attempts to address that challenge.

To do this, the book integrates energy data analysis, engineering design, life-cycle economic cost-effectiveness and environmental impact assessment, as well as planning and policy measures. The book is the result of a combined sixty-five years of teaching and researching energy patterns, efficient and renewable energy systems, and energy planning and policy. It has six sections:

I. Energy Patterns and Trends
II. Energy Fundamentals
III. Buildings and Energy

IV. Sustainable Electricity
V. Sustainable Transportation and Land Use
VI. Energy Policy and Planning

The book's first section provides "energy literacy" for the user by reviewing the importance energy plays in our economy, our environmental quality, and our quality of life; our current patterns of global and U.S. production and consumption; and future scenarios for energy. The second section provides a primer on energy physics, engineering, and economics as it relates to our production, conversion, and consumption of energy.

Sections III, IV, and V explore the energy technologies and opportunities in three of our most important energy sectors: buildings, electricity, and transportation. There are some policy issues discussed in the first five sections of the book, and policy and planning are the focus of section VI. It presents fundamentals of energy policy and the critical role of public policy and consumer choice in transforming energy markets to greater sustainability. Energy is one of the most complex problems of the new century, and the book argues that sustainable energy is within our grasp and uses current developments in technology, planning, and policy as hopeful signs.

Another premise of this book is that you cannot understand energy without understanding the numbers. Techies appreciate this; fuzzies may not. Throughout the book, analytical methods for energy and economic analysis aim to give users a quantitative appreciation for and understanding of energy systems. The emphasis is on simple, practical, mostly back-of-the-envelope and spreadsheet-based tools for design, sizing, and analysis of small-scale systems, including assessment of economic cost-effectiveness. In addition to analytical methods, the book uses case studies extensively to demonstrate current experience and illustrate the possibilities.

In late 2007, energy has become a fast moving field. While the intent of this book is to deal with basics and not fads, it also aims to articulate the prospects and possibilities we now face. Therefore, it is necessary to deal with recent developments in buildings (e.g., Green Buildings, "zero-energy buildings"), electricity (e.g., distributed energy, rooftop photovoltaics, wind farms, vehicles-to-grid), and transportation (e.g., plug-in hybrid, all-electric, and flex-fuel vehicles; biofuels; and transit-oriented land development), potential integrating notions such as Whole Community Energy, and energy policy (the significant energy and climate action by U.S. states and localities and the European Union).

But the energy world continues to change rapidly, and serious students of energy must work to keep up with new developments. As we finish this manuscript at the end of 2007, the global community has agreed in Bali to take the next steps to reduce GHG emissions beyond the Kyoto agreement, and the U.S. Congress has approved the latest federal energy act. Most analysts believe both of these initiatives fall well short of the policy actions needed for a timely transition to sustainable energy.

We encourage users of this book to consult the book Web site http://energyforsustainability.org for valuable links to updated and supplementary information. The Web site also contains an instructor's guide including problem sets and discussion questions to assist teaching and learning the book's practical analytical tools and planning and policy approaches.

Acknowledgments

This book is our own, but it also builds on a foundation of incredible work by countless institutions, organizations, and individuals, all are dedicated to the quest for sustainable energy. Their efforts have affected how we envision our energy situation and future, and many of the products of their work are reflected in this book. Their work is an inspiration not only for our work but also for the future of the world.

Among the individuals, we must list Donald Aitken, Peter Calthorpe, Ralph Cavanaugh, Howard Geller, Denis Hayes, John Holdren, Daniel Kammen, Skip Laitner, Amory Lovins, Stephen Nadel, Arthur Rosenfeld, and Robert Socolow, to name but a few.

Among the organizations and associations, we acknowledge the work of the American Council for an Energy Efficient Economy (ACEEE), the American Wind Energy Association (AWEA), the International Solar Energy Society (ISES), the Natural Resources Defense Council (NRDC), the Pew Center for Global Climate Change, the Renewable Fuels Association (RFA), the Rocky Mountain Institute (RMI), the Union of Concerned Scientists (UCS), and the U.S. Green Building Council (USGBC).

And among international and governmental agencies, the following continue to expand our understanding of the complex energy issues we face: the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), the European Commission, the California Energy Commission, and the U.S. Department of Energy and its many arms, including the Energy Information Administration (EIA), the National Renewable Energy Laboratory (NREL), the Lawrence Berkeley Laboratory (LBL), the Oak Ridge National Laboratory (ORNL), and the other national labs.

We also wish to thank the Island Press staff for their insights and expertise in bringing this project to fruition, especially Todd Baldwin, Emily Davis, and Katherine Macdonald. In addition, the Black Dot Group for project management and copyediting.

Finally, we thank our many colleagues and students who have inspired and pushed us to think through and think anew about sustainable energy and its many dimensions in science, technology, economics, planning, policy, and society.

Section I

Energy Patterns and Trends

CHAPTER 1

The Energy Imperative and Patterns of Use

Energy is the keystone of nature and society. All life on Earth is made possible by incident solar energy captured and stored by plants and passed through ecosystems. Human civilization was spawned by innovation in acquiring and using diverse sources of energy, first by cultivating plants and domesticating animals and eventually by building machines that could use energy stored in fossil fuels. In fact, each phase of development of civilization was triggered by changes in energy use that provided opportunities for growth of human populations and economic systems.

Today, human society is in an unprecedented growth period. Since 1850 and the dawn of the Industrial Revolution, the population, the economy, and energy use have surged, fueled by oil, natural gas, and coal. This growth will soon be limited by diminishing availability of oil and gas and environmental constraints on fossil fuel use, probably sooner than most realize.

Some envision catastrophe ahead, characterized by abrupt climate change resulting from increasing carbon emissions from fossil fuel consumption, or constraints on oil and natural gas supplies, or political and military upheaval over access to energy resources, or economic depression triggered by increasingly volatile and rising energy prices, or all of the above.

Others see our beginning a period of transition to stabilized population and sustainable energy. **Sustainability** is defined as patterns of economic, environmental, and social progress that meet the needs of the present day without reducing the capacity to meet future needs. **Sustainable energy** refers to those patterns of energy production and use that can support society's present and future needs with the least life-cycle economic, environmental, and social costs. By **life cycle,** we mean the cost of a product from acquiring its original raw materials to manufacturing, transporting, and using it to its final demolition and disposal. Life-cycle analysis is fundamental to sustainability because it aims to capture full costs over an extended time period.

Global population is currently forecast to rise to about 9 billion by 2050 and stabilize by 2100. Although there is a huge appetite for more energy, especially among developing countries, ultimately the current growth in energy use may slow along with slower population growth. Population stabilization and slower energy growth do not mean that economic growth would also subside: as energy efficiency improves and structural changes in the economy continue to divorce it from growth of energy, labor, and materials, the economy may continue to grow despite slower population and energy growths.

The critical uncertainty is whether the transition in population and energy use will occur soon enough to avoid a potentially catastrophic situation. Already we are witnessing the symptoms of climate change, energy price volatility, and political turmoil.

In the years before his untimely death in 2005, Nobel Laureate Richard Smalley (2005) characterized the world's quest for sustainability in the following ten prioritized problems:

1. Energy
2. Water
3. Food
4. Environment
5. Poverty
6. Terrorism and war
7. Disease
8. Education
9. Democracy
10. Population

Smalley argued that energy tops the list because abundant, available, affordable, clean, efficient, and secure energy would enable the resolution of all the other problems. We need energy to reclaim and treat water, grow food, and manage the environment. If we can provide food, water, and a clean environment, we need energy to arrest poverty and disease and expand education and communication. By meeting these basic needs, we can control the root causes of terrorism and war, expand democracy, and stabilize population. Energy is the key for achieving a sustainable world system.

Our need for energy to create order in the world stems from the second law of thermodynamics, which states that matter and energy tend to degrade into an increased state of disorder, chaos, or randomness. Only through a flow of quality energy through the system (and a corresponding flow of lower-quality energy out) can order and structure be created. A constant flow of energy is required to maintain that order. Nature and human society on Earth are able to produce order and structure only through their ability to acquire energy. Chapter 4 will cover this fundamental principle in greater detail.

1.1 Our Energy Dilemma

Today we have an energy dilemma. Simply put, our energy problem has three components:

- *Oil*—37% of world energy still comes from petroleum. Reserves are concentrated in the politically volatile Middle East, and the date when conventional oil production will peak looms closer.
- *Carbon*—The global climate is already changing due to carbon emissions from fossil fuels, which still provide 86% of our energy.

- *Expanding global demand*—The developing world needs more energy to achieve basic needs. China's energy use is doubling every decade. Global energy usage grew by 2% per year from 1970 to 2002 and 4.1% per year from 2002 to 2005.

And there are three complicating factors:

- *Progress is slow* toward alternatives to oil, carbon, and growth in demand. We are nearly as dependent on fossil fuels now as we were in the 1970s. Although demand growth in developed countries has slowed, it has been offset by the increasing demand in the developing world. World energy usage nearly doubled from 1975 to 2005, and we remain dependent on fossil fuels, especially oil.
- *Change is hard* because of uncertainty, social norms, and vested interests. Transition to sustainable energy faces barriers to change, including uncertainty about supply options and their impacts, economic and political interests that fight to protect their status quo, and people resistant to changing their behavior. Consumers continue to desire bigger cars and houses and more energy-consuming products.
- *Time is short.* The time to act was yesterday. Over the past three decades, the economy and environment have provided clear signals that our energy patterns are not sustainable. Despite these warnings, we have done little to alter our patterns of use.

In this chapter we provide background necessary to understanding the importance of energy in history and the current global and U.S. energy situations. After giving a historical view of changing energy patterns that parallels the development of human civilization, we describe recent patterns and trends of energy production and consumption. Then in Chapters 2 and 3 we discuss the environmental, geologic, and geopolitical implications of these energy trends and a number of future energy scenarios based on different assumptions of energy demand, economic factors, and policy directions, including scenarios that may accelerate the transition to a sustainable energy future.

1.2 Historical Perspective: Energy and Civilization

It is interesting to trace the history of human society and see how major milestones in population growth, technology, living standards, and economy are linked to changes in our ability to acquire and convert energy for useful purposes.

The discovery of striking stones to ignite fires for thermal uses, perhaps 100,000 years ago, appears to be the first conscious human-engineered energy conversion. The invention of the wheel and stone tools and the domestication of work animals extended mechanical energy uses in the period 8000 B.C. to 4000 B.C. From 4000 B.C. to 1000 B.C., thermal energy from wood fire, then coal, not only provided warmth and cooking but also was essential in developing both ceramic and metal materials, such as pottery (4000 B.C.), bronze (2500 B.C.), and iron (1500 B.C.).

After the start of the first century A.D., devices to harness water and wind power extended human ability to use mechanical power for grist milling and water pumping. There were 10,000 windmills and 5,600 water mills in England by A.D. 1400. The first windsail-driven boats were used by Egyptians about 2000 B.C., but advanced sailing after A.D. 1250 ushered in the age of trade and exploration.

Coal and certain oils were used for heat and illumination since A.D. 100. Coal and oil were later put to a different use as fuel for the newly developed steam engine of the 1800s, and later other heat and mechanical engines, which revolutionized industry, transportation, and mechanized agriculture. The first commercial oil well (1859), invention of the internal combustion engine (1877), oil discoveries in Texas (1901) and Iran (1908), invention of the airplane (1903), and the Model T and assembly production (1908) ushered in the age of petroleum, the automobile, and air transport.

The electrical age had its founding in the invention of the generator and motor (1831) but waited for further inventions of the electric light (1879), refrigeration (1891), and air-conditioning (1902), and development of electric companies and transmission (first in 1891), before taking off after 1920 and revolutionizing living standards.

After 1950, further growth of fossil fuels, electricity (including nuclear power), and related technologies for electronics and telecommunications, agriculture, manufacturing, and transportation, set the stage for global expansion and unprecedented population and economic growth.

Human population had been constrained to 1 billion people by 1800 by limits on energy use and technology. Before 1850, society had to rely on human and animal labor to plow fields, harvest crops, chop firewood, mine and haul coal, and transport people and materials. This drove the market not only for draft animals, but also for human African slaves in the United States and elsewhere. But after 1850, advances in industry, agriculture, transportation, and communication brought about by new energy technologies, freed society from the constraints of slave and animal labor and expanded agricultural and industrial productivity. Human population ascended to 2 billion by 1927, 4 billion by 1974, 6 billion by 1999, and 6.6 billion by 2007.

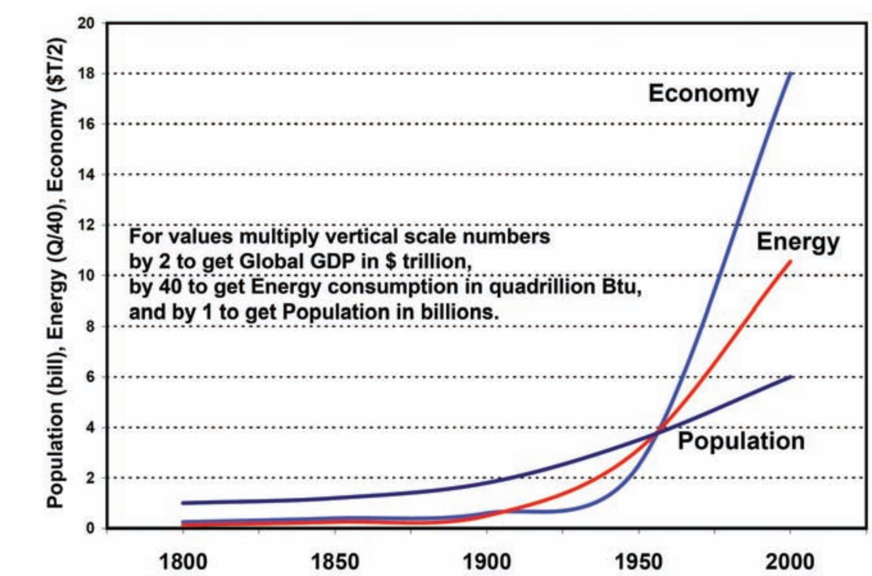
The world economy grew (in constant dollars) from an estimated $100 billion in A.D. 1 to $700 billion in 1820. The Industrial Revolution spawned a fivefold increase by 1970 to $3,500 billion, then another tenfold increase from 1970 to 2000 to $36,000 billion (OECD, 2001). Prior to 1980, most energy analysts believed energy consumption and economic growth were inextricably correlated, but after 1980 economic product grew far faster than both energy consumption and population. Higher energy prices and new technologies led to greater energy efficiency, and the service and information sectors grew faster than the energy- and material-intensive manufacturing sectors of the economy.

Table 1.1 and Figure 1.1 show the huge growth in population, economy, and energy use since 1800. These exponential growth rates are impressive historically as they have changed the nature of the world in which we live; but they are equally impressive as we look to the future and consider how we can sustain them, modify them, and live with the consequences.

table 1.1 Global Energy through History and Its Relationship to Population and the Economy

Date	Population	Economy	Energy Age
< A.D. 1	<0.3 billion	<0.1 T$	Human, animal power; wood thermal
1–1800	<1 billion	<0.7 T$	Human, animal power; wood/coal thermal; wind/water
1800–1900	1.5 billion	0.9 T$	Coal/steam power, telegraph, railroad, Industrial Revolution
1900–1950	2 billion	2.0 T$	Petroleum and electrical ages begin; automobile, telephone, air travel
1950–1980	4 billion	4.0 T$	Nuclear power; intensive agriculture, computer, space exploration
1980–2000	6 billion	36.0 T$	Information Age; energy and economic growth rates begin to diverge

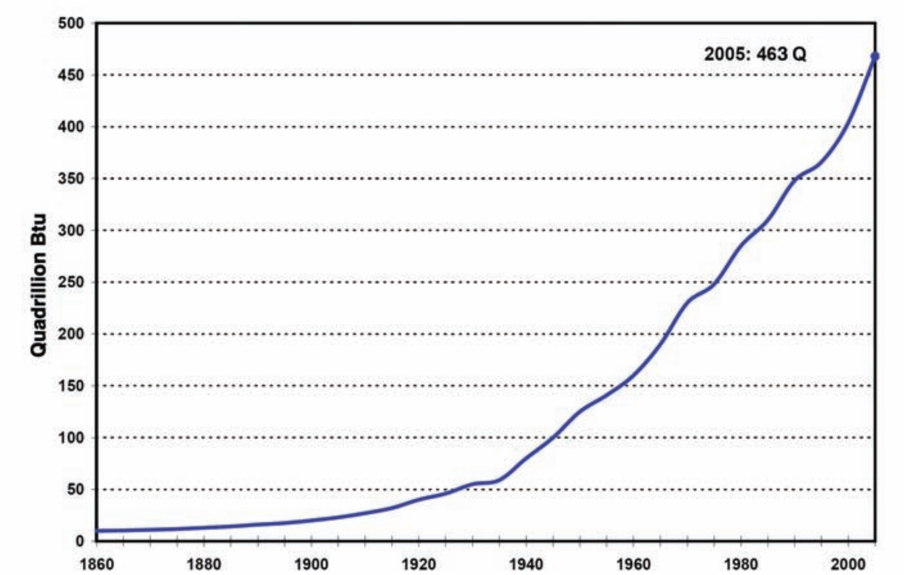
figure 1.1 Global Growth of Population, Energy, and Economy, 1800–2000



1.3 Global Energy Supply and Consumption

From this long-term perspective, let's zero in on the past several decades until today so that we can understand the current energy situation. We will look separately at global energy and U.S. energy. In Chapters 2 and 3, we will explore the implications of this situation and what it bodes for the future.

figure 1.2 World Energy Consumption, 1860–2005



1.3.1 Explosive Growth of Energy, Inequitably Distributed

Energy supply and demand has exploded in the last century. As it has done so, our reliance on fossil fuels has grown. Not coincidentally, so has the disparity of use between industrialized and developing countries. Figure 1.2 shows the tremendous growth in commercial energy since 1860, especially since 1940. Consumption doubled from 1970 to 2005, growing at 2% per year until 2002 and 4.5% per year from 2003 to 2005, when consumption reached 463 quadrillion (10^{15}) British thermal units (Btu), or 463 quads. A **Btu** is a traditional English unit of energy equal to 1054 joules, the standard metric unit, and 0.293 watt-hour, the standard unit of electrical energy. A quad is one quadrillion (10^{15}) Btu and is a standard unit for national and global energy production and consumption used by U.S. energy agencies. Chapter 4 discusses energy units and conversion.

This rate of growth is likely to continue because of the expected demand by developing countries for energy. These countries have a big appetite for energy because of the current economic and energy disparity among rich and poor countries, shown in Table 1.2. Annual energy use worldwide averaged 72 million Btu per capita in 2005. While the developed countries, with 20% of the world population, consume energy at an annual rate of more than 150 million Btu per capita, the developing countries with 80% of the population, consume energy at a rate of less than 40 million Btu per capita. The average U.S. citizen consumed 340 million Btu in 2005; the average Japanese and Brit consumed about 170 million Btu; the average Chinese 51 million Btu (up from 33 in 2002); the average Indian 15 million Btu; the average Bengali 5 million Btu; and the average Ethiopian 1 million Btu per person.

table 1.2 **Indicators of Energy, Economy, and Population for Selected Countries and the World, 2005**

	Energy	Energy/GDP*	Energy/GDP**	% Pop	% Energy	% GDP*	% GDP**	% CO_2
Canada	**436**	17.4	13.8	0.5%	3.1%	2.3%	1.8%	2.2%
United States	340	9.1	9.1	4.6%	**21.8%**	**30.4%**	**19.2%**	**21.1%**
Australia	273	12.1	9.0	0.3%	1.2%	1.2%	1.1%	1.4%
Sweden	260	8.7	9.0	***0.1%***	0.5%	0.7%	0.4%	0.2%
Russia	212	**86.7**	**14.9**	2.2%	6.5%	1.0%	3.5%	6.0%
France	182	8.0	7.2	1.0%	2.5%	3.9%	2.7%	1.5%
Korea, South	191	14.5	12.5	0.8%	2.0%	1.8%	1.3%	1.8%
Germany	176	7.4	7.0	1.3%	3.1%	5.4%	3.6%	3.0%
Japan	177	***4.5***	6.5	2.0%	4.9%	13.8%	6.0%	4.4%
United Kingdom	166	6.1	6.0	0.9%	2.2%	4.5%	2.9%	2.0%
South Africa	114	31.5	10.0	0.7%	1.1%	0.4%	0.9%	1.5%
Mexico	65	10.8	6.6	1.6%	1.5%	1.8%	1.8%	1.4%
Brazil	50	13.9	6.3	2.9%	2.0%	1.8%	2.6%	1.3%
China	51	35.8	7.9	**20.3%**	14.5%	5.2%	14.7%	18.9%
Indonesia	23	25.3	5.8	3.6%	1.2%	0.6%	1.6%	1.3%
India	15	24.8	4.0	17.0%	3.5%	1.8%	7.0%	4.1%
Pakistan	14	30.0	5.3	2.5%	0.5%	0.2%	0.7%	0.4%
Nigeria	8	16.7	6.6	2.0%	0.2%	0.2%	0.3%	0.4%
Bangladesh	5	11.8	***1.1***	2.2%	0.1%	0.2%	1.1%	0.1%
Ethiopia	***1***	11.0	1.5	1.1%	***0.0%***	***0.0%***	***0.1%***	***0.0%***
World	**72**	**12.7**	**8.0**	**6,445**	**463**	**43,920**	**55,500**	**28,193**
units	million	1000Btu/$GDP	1000Btu/$GDP	million	quad Btu	billion $	billion $	million

Highest values in **bold**; lowest values in ***italic bold***
* GDP data based on market exchange rates, a traditional measure of GDP.
** GDP data based on product purchasing power, which more accurately reflects strength of the national economy.
Source: U.S. EIA (2007), *International Energy Annual 2005*

Table 1.2 gives other indicators of energy use disparity. The United States, with less than 5% of the world's population, accounted for 20 to 22% or about 4 to 5 times its share of the world's energy consumption, economic output, and carbon dioxide emissions in 2005. This disparity in energy use is important. It is an indicator of the economic and social disparity in the world, and we will never achieve a sustainable world system until basic human and societal needs for food, education, employment, transportation, and other necessities are met. As developing countries advance, they will require a huge increase in their energy use to fuel the industry, transportation, electrification, telecommunications, and human services to provide these basic needs.

One hopeful sign is that the United States and other countries have reduced the energy intensity of their economies (see Equation 1.1). **Energy intensity** indicates how much a national economy is dependent on energy per unit of economic output, or gross domestic product (GDP). It is measured in energy/$GDP. If energy intensity is low, then energy efficiency is high in that economy. Since 1980, global energy intensity has decreased by 25% (Figure 1.3); the United States has improved by 35%. Although the U.S. economy is considerably more energy intensive than those of Japan, Germany, France, the United Kingdom, and Sweden, it is ten times more energy efficient than Russia's economy based on energy/$GDP.

Eq. 1.1

$$\text{Energy intensity} = \frac{\text{energy used}}{\$\text{GDP}}$$

Figure 1.3 plots indicators of change from 1980 to 2004 on a scale normalized to 1980 values. The graph shows the large increase in the global economy, which has outpaced population by 80%, and the 45% increase in carbon dioxide emissions since 1980. Energy consumption growth has tracked population growth very closely, and this is shown in energy/capita that has been relatively constant.

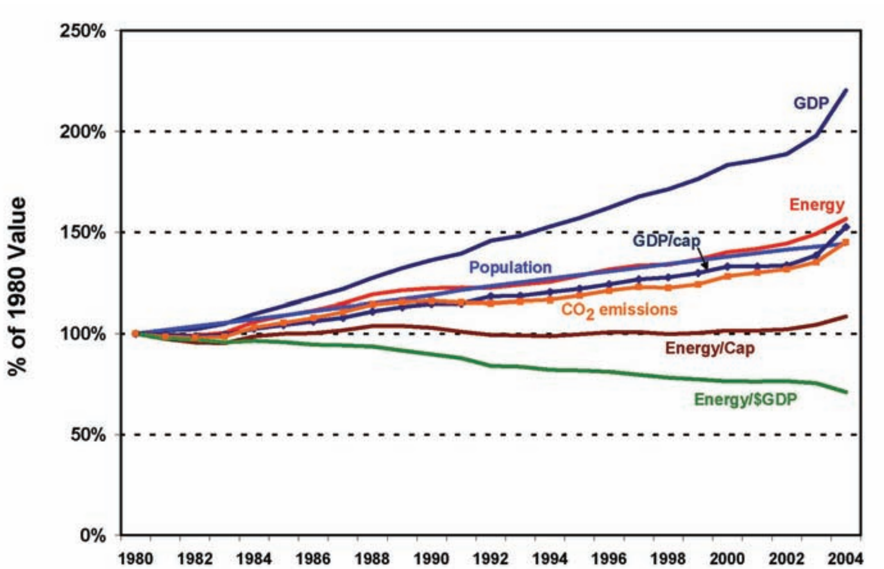
Eq. 1.2

$$\text{Average energy per capita} = \frac{\text{energy used}}{\text{Person}} = \frac{\text{Total energy used}}{\text{Total population}}$$

Total energy used ← Increase in developed countries

Total population ← Increase in developing countries

figure 1.3 Global Indicators of Change, 1980–2004



Energy consumption, population, GDP, energy/capita, GDP/capita, energy intensity, carbon dioxide emissions.

Source: data from U.S. EIA, 2007b

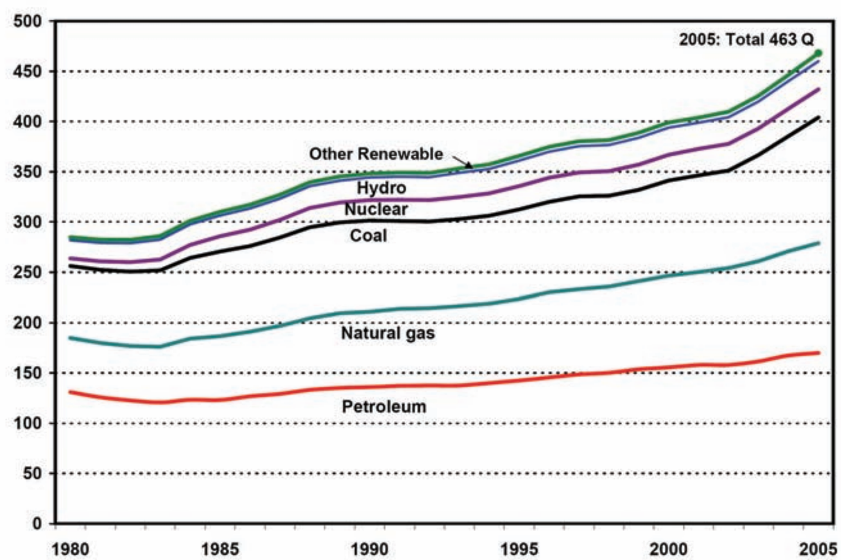
Average energy/capita is calculated by dividing total energy consumption by total population. This average disguises the high variance among developed countries (e.g., 436 for Canada) and less developed countries (e.g., 1 for Ethiopia). The average has remained constant because both energy used (the numerator in Equation 1.2) and population (the denominator) grew. The energy increased primarily in developed countries and population grew primarily in the less developed countries, so they offset each other to produce a near constant average energy per capita worldwide between 1980 and 2000, even though the disparity increased.

1.3.2 Continuing Dependency on Oil and Fossil Fuels

In 1973, the world got a wake-up call on the geopolitics of oil. The Organization of Petroleum Exporting Countries (OPEC) increased its influence on oil markets and the Arab oil embargo of the United States sent oil prices skyrocketing. Oil shocks in 1980 and 1991 gave a similar message about the volatility of oil supply and price, but the sources of world energy have changed little.

As Figure 1.4 shows, the world relied on fossil fuels for 90% and on oil for 46% of its commercial energy in 1980. However, those percentages dropped only slightly by 2005, to 86% and 37%, respectively. And in quantity, world oil consumption increased 33% and total fossil fuels increased 40% in that time, with a corresponding increase in carbon dioxide emissions.

figure 1.4 World Energy Consumption by Source, 1980–2005



Source: data from U.S. EIA, 2007b

Other sources of energy have not made a difference. Nuclear power grew to 6.5% by 1990, but has slipped to 5.9% in 2005. Hydroelectric power has not grown, and renewable power from wind, solar, geothermal, and biomass electricity, despite fast growth since 1999, has yet to make an impact.

The bottom line is that, despite fossil fuel price volatility and supply disruptions, political conflicts affected by access to energy resources, and increasing recognition of the dangers of continued fuel combustion emissions on global climate, the world has done little to change its fossil-fueled patterns of energy use. Despite skyrocketing prices pushing $100/barrel, world oil demand in 2007 is rising twice as fast as in 2006 and is expected to hit 88 million barrels per day by the end of 2007.

With 20% of the world population consuming 75% of the world energy and controlling 75% of the global economy, while the poorest 80% struggle toward development, we are far from an equitable energy and economic system. Perhaps the best news in these trends is that our global economy has become less energy intensive through efficiency improvements and structural change. If this can be translated to the developing world, perhaps their economic advancement can occur without the large energy requirements experienced by the industrialized world.

Still, the material and energy requirements needed to support the physical infrastructure to provide for basic needs of very large populations will be enormous, and global energy consumption will have to grow considerably. Chapters 2 and 3 explore some of consequences of that growth and our future options.

1.4 U.S. Energy Supply and Consumption

We should investigate U.S. energy patterns in greater detail. The United States is the world's largest energy consumer, and its behavior has a significant influence on other developed and developing nations. In addition, if we are to avoid or delay looming impacts of these patterns as the rest of the world develops, there is no better place to start our investigation than by examining the United States.

There are volumes of data and analyses of U.S. consumption and production available from various sources, especially the U.S. Energy Information Administration (EIA), an arm of the Department of Energy (DOE). Using EIA data, this section highlights three dramatic trends that characterize the U.S. energy situation:

1. *Energy intensity of the economy has steadily declined while energy use per capita has remained constant.* This is good news. We are getting far more economic output from our energy, and we are not increasing our average use of energy per person despite driving more, occupying bigger houses, and using more energy gadgets, such as cell phones and computers. In other words, we are getting more out of the energy we use.
2. *Electricity has increased significantly, and 92% of it is generated by steam power that is inherently inefficient.* Electricity is increasingly the source of choice because of its multiple uses

and convenience. But fossil-fuel and nuclear steam power requires three units of source energy for every one unit of electricity generated, and these electricity losses amount to more than 27% of our total energy use.

3. *Oil imports have increased dramatically due to rising consumption for transportation and declining domestic oil production.* Two-thirds of United States oil is now imported from other countries, and this is likely to increase as the United States runs out of conventional oil reserves.

1.4.1 U.S. Patterns of Energy Consumption and Production

Before looking more closely at each of these issues, it is important to understand some basic patterns of energy production and use. If we are to achieve more sustainable energy use patterns, we need to know where our energy comes from and how we use it. We need to be able to access energy data and analyze them to answer questions about past trends and current uses. Solution Box 1.1 gives a short primer on accessing and interpreting energy data.

Figure 1.5(a) indicates the historic growth of energy consumption relative to domestic production and the sources of energy used. Total consumption doubled from 1950 to 1973, but the oil shocks of 1973 and 1980 led to higher prices, economic recession, and temporary declines in energy consumption. Since the early 1980s, energy use increased to about 100 quads per year in 2003–2007.

Consumption has outpaced domestic energy production, and the growing gap (30% in 2005) must be met with net imports, almost entirely petroleum. Figure 1.5(b) shows the sources of energy use in the United States from 1950 to 2006. The United States is nearly as dependent on fossil fuels today (85% in 2007) as it was in 1973 (93%). We have nearly doubled our use of coal in that time.

Oil and natural gas use declined with higher prices from 1975–1985, but use has increased since 1985. Oil is no longer used as much to generate electricity or heat buildings, and its growth is attributed to increased use in vehicles for transportation. Petroleum use reached a record high of 20.8 million barrels per day in 2005. In 2006, despite higher crude oil and gasoline prices, oil still contributed 40% of total U.S. energy.

Other sources are still small compared to the fossil fuels. Figure 1.5(b) shows that nuclear power has grown steadily since 1970, but still amounts to only 8% of total energy in 2006. No new nuclear plants have been added since the 1980s. Renewable energy still amounts to only 7% of total energy consumption in 2006. This includes hydroelectric production; wood, waste, ethanol, and other biomass energy; and commercial wind and solar electricity. Noncommercial biomass, such as residential wood heat, and solar heating are not included in these figures.

Figure 1.6 shows the sources and distribution of consumed energy to various sectors in 2005, and Figure 1.5(c) gives the trends in consumption in each sector. Industry is still the largest user (32%), but total industrial use has remained about the same since the 1970s,

SOLUTION

SOLUTION BOX 1.1

Accessing and Interpreting Energy and Related Economic Data

Most of the energy data presented in this chapter come from the databases of the U.S. Department of Energy's Energy Information Administration (EIA) (http://www.eia.doe.gov/) and the International Energy Agency (IEA) (http://www.iea.org/). Some additional economic data come from the U.S. Bureau of Economic Analysis (BEA) (http://www.bea.doc.gov/). To answer simple questions about energy production and consumption patterns and trends, energy analysts must know how to access data and conduct simple statistical calculations.

EIA data are well organized through two annual reports. The Annual Energy Review (AER) outlines domestic consumption by fuel and use sector, production by fuel, imports by source country, and energy resource data from 1949 to the most current year. The AER is produced in August each year with the previous year's data. More recent monthly data are provided in EIA's Monthly Energy Review (MER) and several other fuel-specific monthly reports. Data are given in tabular and graphical HTML and PDF formats, as well as downloadable spreadsheet format. EIA's International Energy Annual and the International Energy Agency provide online energy data for countries and regions, and a variety of other fuel- and country-specific information.

Accessing and downloading data is one thing but presenting and interpreting data is another. Most interpretation requires simple analysis including indicators such as averages, quantity per capita, energy per $GDP, and so on. Trend analysis incorporates time in the calculations and often uses percent change and average annual percent change as important indicators. The list below gives some simple equations for such analysis.

1. Average of a number of values of *A:*

$$\textbf{Average (mean)} = \frac{\textbf{Sum of } A}{\textbf{\# Values}} = \frac{(\Sigma A)}{N}$$

where A = value

N = number of values

What is the average energy consumption of the top five energy consuming countries in Table 1.2?

Solution: The top five countries (from Table 1.2, column 5): United States, 21.8%; China, 14.5%; Russia, 6.5%; Japan, 4.9%; Germany, 3.1%.

$$\textbf{Country Consumption} = \textbf{\% Energy/100} \times \textbf{Total World Energy}$$

$$\textbf{Average} = \frac{\Sigma\textbf{Country Consumption}}{\textbf{\# Countries}} = \frac{(\Sigma\textbf{Country\%Energy/100}) \times \textbf{TWE}}{\textbf{\# Countries}}$$

$$\textbf{Average} = \frac{(0.218 + 0.145 + 0.065 + 0.049 + 0.031) \times 463Q}{5} = \frac{(0.508) \times 463Q}{5} = \textbf{47 quads}$$

2. % change in values between time 1 and time 2:

$$\textbf{\% change} = 100\left(\frac{V_2}{V_1} - 1\right)$$

where V_1 = value at time 1
V_2 = value at time 2

The EIA data show that the United States consumed 84.60 quads in 1991 and 98.16 quads in 2003. What is the percent change in consumption during those 12 years?

Solution: $\textbf{\% change} = 100\left(\frac{98.16}{84.60} - 1\right) = 100\,(1.160 - 1) = 100\,(0.160) = 16.0\%$

3. Value at time 2 with constant or average periodic (e.g., annual) growth rate from time 1:

$$V_2 = V_1(1 + r)^n$$

where r = periodic (e.g., annual) growth rate
n = number of periods (e.g., years)

4. Average periodic (e.g., annual) growth rate from value at time 1 to value at time 2:

$$r = \left(\frac{V_2}{V_1}\right)^{1/n} - 1$$

where r is given as a decimal rate and the %rate = $R = 100r$

What is the average annual rate of change in U.S. consumption between 1991 and 2003?

Solution: $r = \left(\frac{98.16}{84.60}\right)^{1/12} - 1 = (1.160)^{1/12} - 1 = 1.0125 - 1 = .0125$ **or** $R = 1.25\%$ **per year**

If the U.S. consumption were to continue at the average annual growth rate it had from 1991 to 2003, what would its consumption be in 2010?

Solution: $V_{2010} = V_{2003}(1 + .0125)^7 = 98.16Q(1.0125)^7 = 107.1$ **quads**

5. Doubling time for constant or average periodic rate of growth:

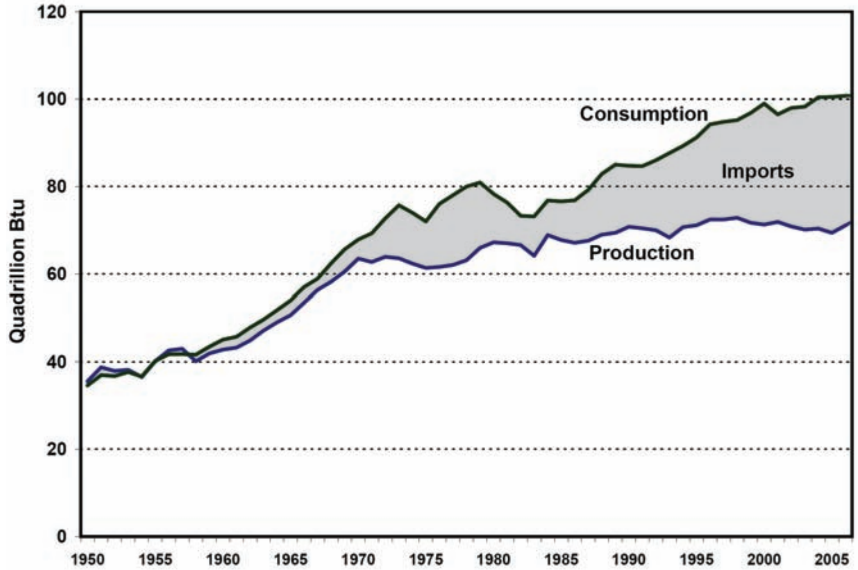
$$DT = \frac{70}{R}$$

where DT = doubling time
R = %rate = $100r$

If the U.S. consumption were to continue at the average annual growth rate it had from 1991 to 2003 ($R = 1.25\%$), in what year would it be double the 2003 consumption, or 196 quads?

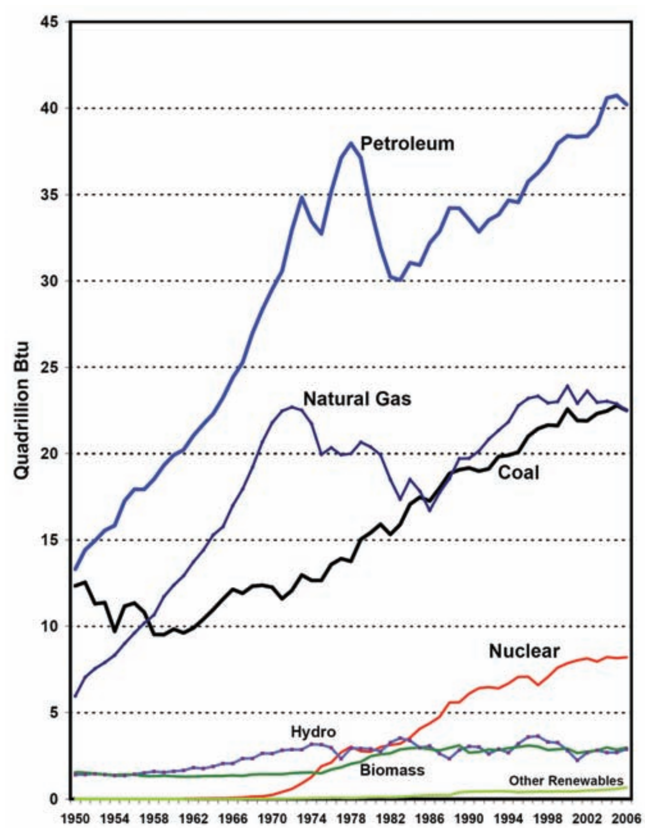
Solution: $DT = \frac{70}{1.25} = 56$ **years or in 2059**

figure 1.5a U.S. Energy: Consumption, Production, and Net Imports, 1950–2006



Note the widening gap between rising consumption and flattening domestic production. The gap (30% of consumption in 2005) is filled with net imports, especially petroleum.

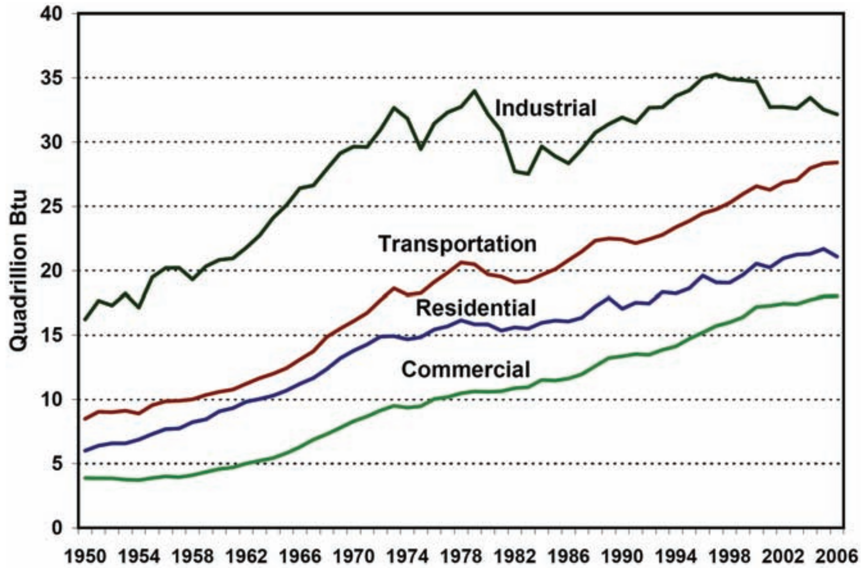
figure 1.5b U.S. Energy Consumption by Source, 1950–2006



Note the continued heavy reliance on fossil fuels (86%), oil (40%), natural gas (23%), and coal (23%) in 2006. Nuclear power contributed 8% and renewable energy 6%.

Source: data from U.S. EIA, 2007a, 2007c

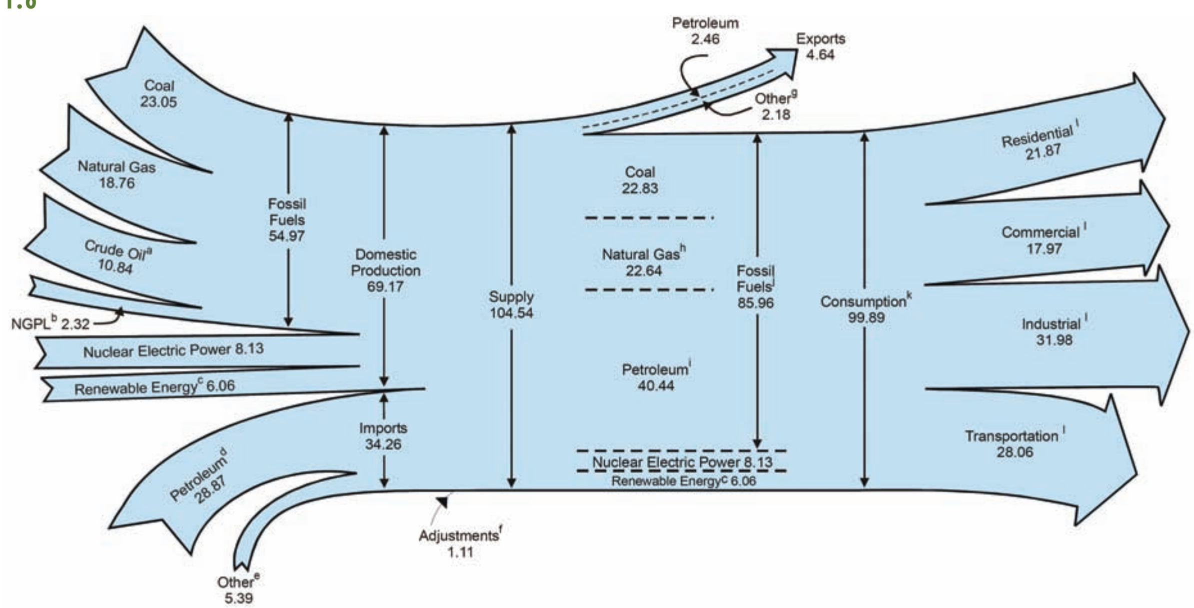
figure 1.5c **U.S. Energy Consumption by Sector, 1950–2006**



Note that industry is still the top energy consumer, but energy for transportation and residential and commercial buildings is rising at a faster rate. Taken together, buildings are the biggest consuming sector.

Source: data from U.S. EIA, 2007a, 2007c

figure 1.6 **Energy Flowchart for United States, 2005**



Energy sources on left and end uses on right: industrial (32%), transportation (28%), residential (22%), commercial (18%). Imports of petroleum are 28% of total consumption.

Source: U.S. EIA, 2007b

despite some ups and downs. About 20% of industrial "energy" is actually used for nonenergy material feedstocks (e.g., asphalt, road oil, petrochemicals, lubricants, solvents). But energy use has grown steadily in all other sectors, especially transportation (now 28% of total use and 70% of oil) and residential and commercial buildings (40% of total use). Any effort to reduce energy demands, oil imports, and carbon emissions must focus on transportation and buildings.

1.4.2 U.S. Energy and Economy: Efficiency and Structural Changes

Amid concerns about stagnant energy production, shrinking domestic reserves of oil, and increasing oil imports, one bit of good news in U.S. energy patterns is that the energy intensity of the economy (see Equation 1.1, p. 10) has improved significantly. The main drivers of this improvement have been energy efficiency and structural changes in the economy.

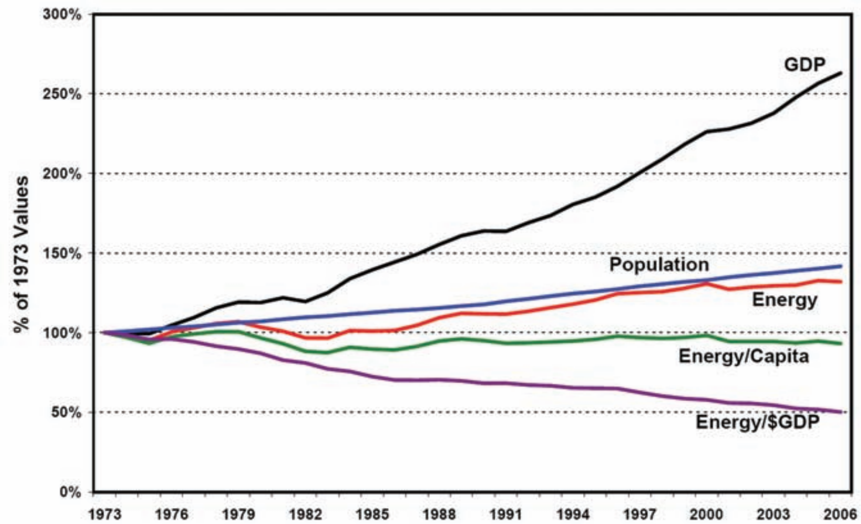
From 1949 to 1973, energy steadily increased from 215 to 358 million Btu per capita, and energy intensity or the energy required per dollar GDP remained constant at 18 to 20 thousand Btu per $GDP. While most analysts in the early 1970s thought energy per capita might level off, many thought energy and economic growth were inextricably tied. Indeed, this theory was supported when both energy use and the economy declined in the mid-1970s and early 1980s. However, writers such as Daniel Bell foretold of structural changes in the economy. His book *The Coming of Post-Industrial Society* (1973) argued that we were moving toward post-industrialism that would be dominated by information, science-based industries, and services rather than material manufacturing.

Much of what Bell suggested has turned out to be true. The information-based economy began in 1980 and took off in the mid-1990s; science- and technology-based industries, such as computer and biotechnology, have grown much faster than traditional industry; and services (financial institutions, commercial services, entertainment, etc.) have become a mainstay of the economy, eclipsing more energy- and material-intensive manufacturing.

These structural changes in the economy to less energy-dependent modes of income generation have been complemented by improvements in energy efficiency. Spurred by new efficiency technologies, higher energy prices, and government mandates and incentives, energy users have invested in efficiency improvements in buildings and equipment that get the same or greater performance with less energy. These improvements have been made to vehicles, motors, furnaces, appliances, electronics, and building envelopes. We will see in later chapters that major opportunities for efficiency improvement remain untapped.

Figure 1.7 gives U.S. economic and energy consumption indicators since 1973. U.S. GDP has grown considerably. Despite four recessionary dips, the economy grew by 160% from 1973 to 2006, while energy use and population grew by about 40%. Energy per capita has remained relatively constant, actually dipping from 358 million Btu in 1973 to 334 million Btu in 2006. However, in constant 2000 $, energy use per $GDP has dropped by half from 17.4 thousand in 1973 to 8.7 thousand Btu per $GDP in 2006.

figure 1.7 **U.S. Energy Consumption Indicators, 1973–2006**



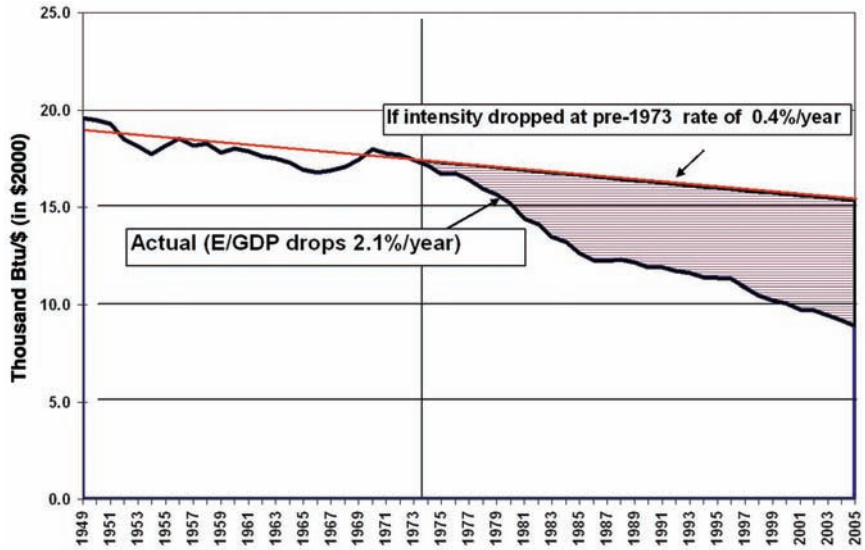
Source: data from U.S. EIA, 2007a, 2007c

As Figure 1.7 shows, the most dramatic drop in energy intensity came in the "energy crisis" period of 1973–1986 and in the period of structural change in the economy from 1996–2000. Between 1949 and 1973, energy and economic growth were closely linked and energy intensity declined by only 0.4% per year. Between 1973 and 1986, however, higher energy prices prompted efficiency investments primarily in industry, vehicles, and buildings, and energy intensity dropped by 2.7% per year. The period from 1986 to 1996 saw minor improvement of 0.7% per year as investment in efficiency declined.

Between 1996 and 2000, the information economy driven by the "dot-coms" surged the economy forward with little increase in energy use, dropping energy intensity at an unprecedented rate of 2.8% per year. Even with the "bust" of the dot-coms and the sluggish economy during 2000–2005, energy intensity continued to drop at a rate of 2.1%. In addition to the lasting effects of the changing economic structure, higher energy prices in this period stimulated investment in efficiency and conservation.

Arthur Rosenfeld of Lawrence Berkeley Laboratory and the California Energy Commission developed Figures 1.8 and 1.9 to illustrate the economic effect of this trend. Figure 1.8 plots the actual drop in energy intensity from 1949 to 2005, and also continues the trend line from 1949 to 1973 (0.4% decline) to 2005. Figure 1.9 shows the resulting energy consumption if the trend to 1973 had continued. The improved energy intensity resulted in saving 70 quads of energy at a value of $0.7 trillion. Rosenfeld attributes one-third of this improvement to energy efficiency improvements in buildings, one-third to vehicle efficiency, and one-third to structural changes in the economy.

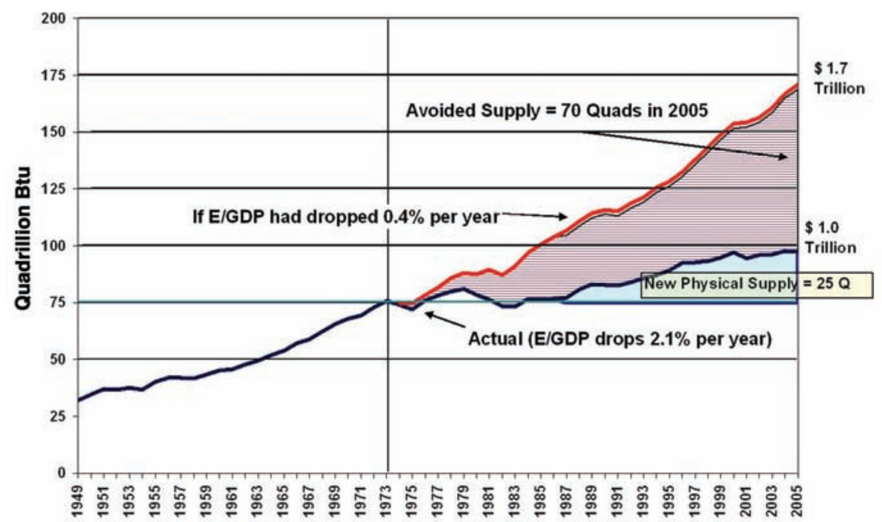
figure 1.8 **U.S. Energy Intensity, 1949–2005**



Actual U.S. energy intensity from 1949–2005 and continued trend line of 1949–1973. In year 2005, E/GDP would have been 16 Btu/$.

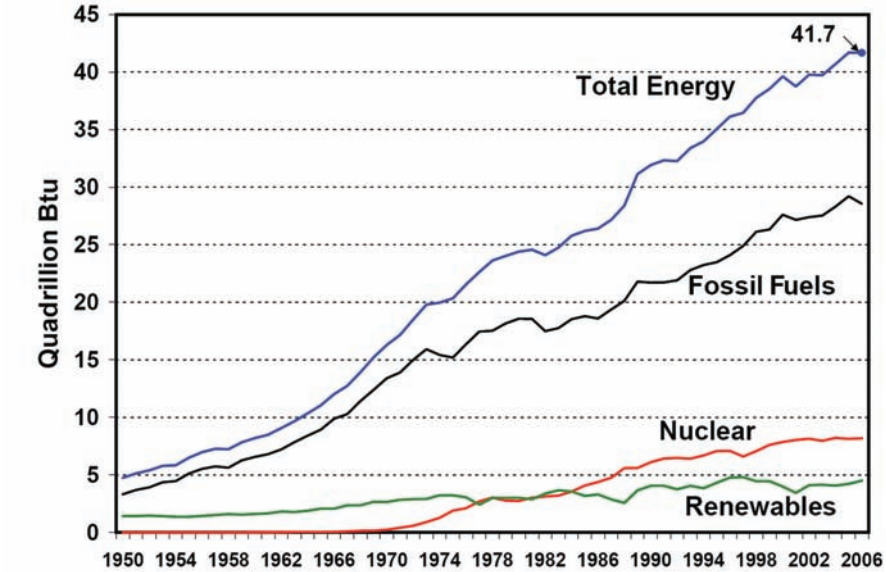
Source: Rosenfeld, 2006, used with permission

figure 1.9 **Effect of Improved Energy Intensity on U.S. Energy Consumption, 1973–2005**



Actual U.S energy consumption and resulting consumption if pre-1973 energy intensity trend had continued.

Source: Rosenfeld, 2006, used with permission figure 1.10 **U.S. Energy Used for Generation of Electricity, 1950–2006**



Continued high growth in electricity fueled mostly by coal (see Figure 1.11).

SOURCE: data from U.S. EIA, 2007a, 2007c

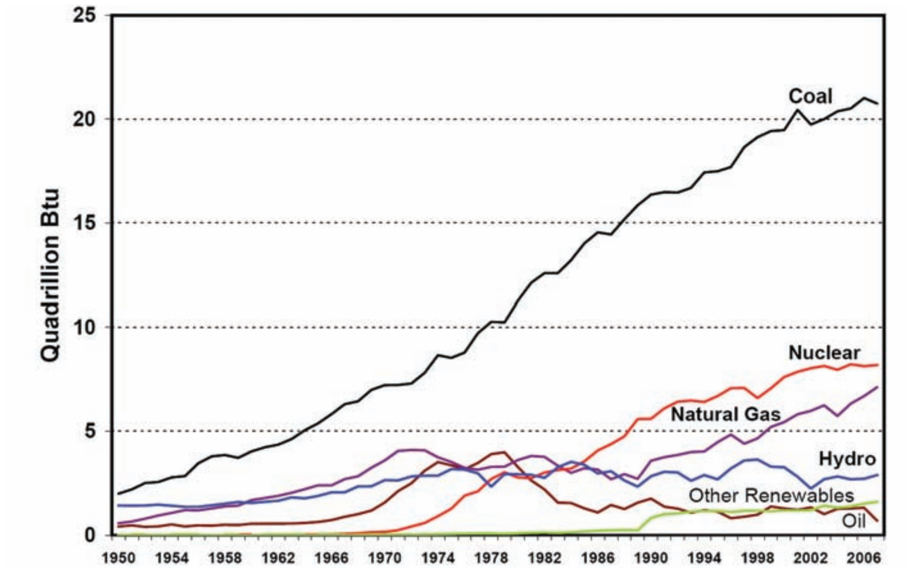
1.4.3 U.S. Electricity: Increasing Energy of Choice and Increasing Energy Conversion Losses

Another important trend in U.S. energy is the increasing reliance on electricity. Electricity is a high-quality form of energy that can be applied to a wide range of uses, including motors and electronics, lighting, refrigeration, heating and cooling, and rail transit. Expanding use of electronics, air-conditioning, and heat pump heating has contributed to electricity's growth. Some foresee further use of electricity for transportation for plug-in vehicles and light-rail transit (see Chapters 10, 13, and 15).

Electricity is versatile not only in its applications but also in its energy sources. It is the only practical way we can currently use coal, nuclear, hydro, wind energy, and solar photovoltaics on a large scale, and we can actually use any other form of energy to produce it, including oil, natural gas, biomass, solar thermal, and geothermal, among others. Although electricity is still our most expensive form of energy, electricity prices have remained relatively stable during the past 30 years when fossil fuels prices have been extremely volatile.

Figure 1.10 shows that total energy for electricity more than doubled from 20 quads in 1975 to 42 quads in 2005. More than 70% of the energy for electricity comes from fossil fuels, and 75% of that is from coal. Energy for electricity comes from coal (52%) and nuclear (20%), but natural gas has grown to 16% of source energy and may overcome nuclear in the

figure 1.11 **U.S. Energy Sources for Electricity, 1950–2006**



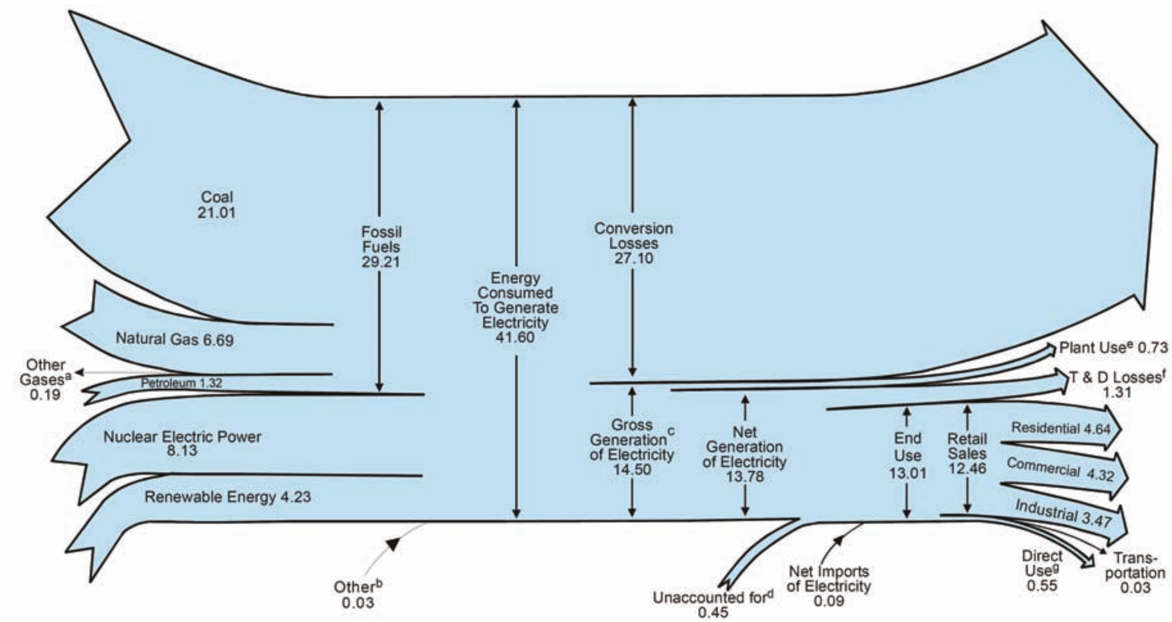
Source: data from U.S. EIA, 2007a, 2007c

next few years (Figure 1.11). Natural gas–fired electricity generating capacity increased by 2 1/2 times between 2000 and 2005 and amounted to 89% of the growth of U.S. generating capacity during that time. Renewable energy contributes only 12% of electricity; this comes from hydro (7%), wood/waste (2.5%), geothermal (1%), and wind/solar (1%).

Excepting hydro, wind, and solar photovoltaic production, 92% of U.S. electricity comes from steam power generation. We will discuss the thermodynamics of power generation later, but suffice it to say here that upgrading low-quality thermal energy of fuel combustion or nuclear reaction to produce steam to spin a turbine and generator to produce high-quality electricity is a losing proposition. As shown in the U.S. electricity energy flow chart for 2005 in Figure 1.12, only 13.01 of 41.6 quads, or 31% of source energy was converted to end-use electricity. The remainder (69%) was lost to thermal conversion (65%) and transmission losses and plant uses (4%).

Because of these large losses, for electricity we make a distinction between end-use energy and primary energy. **End-use energy** is the energy used at the point of use, for example in a building or in a vehicle. **Primary energy** is the original energy needed to produce that end-use energy. For all energy types, there is a difference between primary and end-use energy because it takes some energy to extract, process, and transport energy to the end use. But the difference is by far the greatest for steam-generated electricity, and we must account for the primary energy. In Figure 1.12, end-use electricity in 2005 was 13.01 quads whereas primary energy for electricity was 41.6 quads.

figure 1.12 **Energy Flowchart for U.S. Electricity, 2005**



Note end-use electricity is only 31% of primary energy.

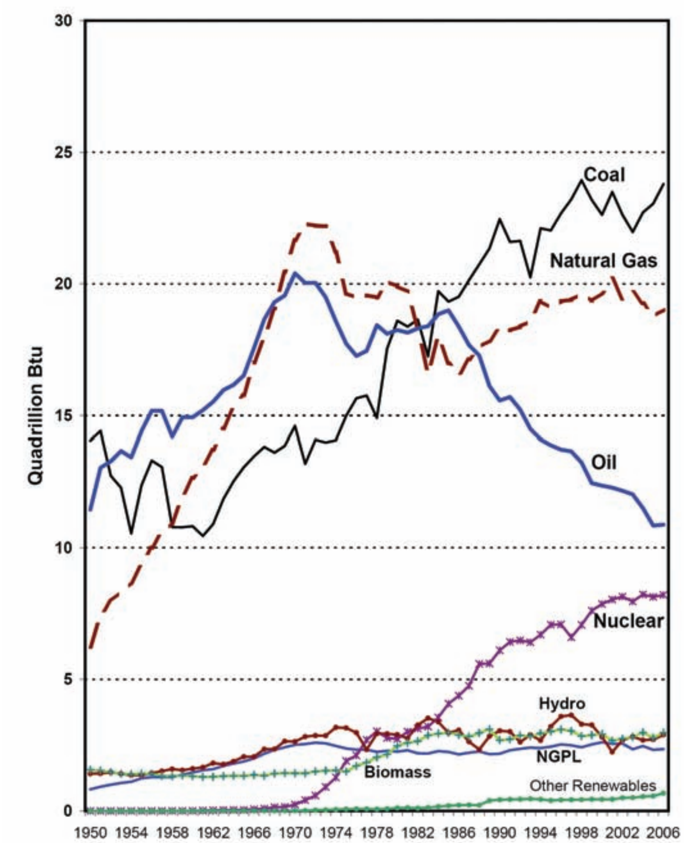
Source: U.S. EIA, 2006

About three-quarters of our electricity is used in buildings with the remainder used for industrial processes. In buildings, electricity for appliances and equipment, lighting, air-conditioning, and space and water heating amounts to about 40% of end-use energy but 66% of primary energy. Energy losses from electricity generation and transmission constitute the largest energy requirement for commercial and residential sectors and the third largest for industry. There are ways to capture some of these thermal losses through combined heat and power (CHP), but this is limited at large central power stations.

One important consideration of this conversion loss issue is that for every unit of steam-generated end-use electricity saved through greater efficiency, three units of primary energy are saved. Because fossil-fueled steam power, especially coal, is a major source of carbon emissions, improving electricity use efficiency also has a three-fold multiplying effect on carbon emission reductions.

1.4.4 U.S. Energy Production Shortfall and Oil Imports

Energy is one of the most important security problems facing the United States. Figure 1.5(a) showed the growing gap between energy consumption and domestic production that must figure 1.13 **U.S. Production of Energy by Source, 1950–2006**



Despite increases in coal and nuclear, total production has been stagnant at 69–72 quads since 1989. Crude oil peaked in 1970 and has steadily declined after a few years of Alaskan production. Natural gas peaked in 1971 but recovered half of its decline from 1985 to 2000.

Source: data from U.S. EIA, 2007a, 2007c

be filled with imported oil. Because our economy and way of life depend on energy, some believe we need to secure access to energy supplies at all costs, even if these supplies may be in other countries. Others believe that we need to close the gap between our consumption and domestic production through both efficiency improvements to temper growth of consumption and new domestic energy supply.

However, domestic production of all energy in the United States has been flat since the late 1980s at 69–73 quads (it was 69 quads in 2005, slightly less than in 1989). Figure 1.13 shows production by source from 1950 to 2006. While coal and nuclear power from uranium have increased since 1970, petroleum and natural gas production both peaked in the early 1970s. Natural gas production has recovered somewhat since 1985, but like oil, it has not kept up with consumption; net imports of natural gas have increased from 4% of consumption in 1986 to 16% in 2005.

Crude oil production continues its steady decline to 5.1 million barrels per day (mbd) (10.8 quads) in 2006, down from 9.6 mbd in 1970. Simply put, the United States is running out of oil.

This declining oil production, combined with the rising petroleum consumption for transportation shown in Figure 1.14, presents the United States with perhaps its most pressing energy dilemma. Oil consumption has declined in all other sectors since the 1970s, but transportation gasoline and diesel fuels have driven significant growth in overall oil use since 1983. Petroleum continues to be the largest source of energy in the United States at 40% of total consumption. Industry is the second-highest user of oil with 25%, and two-thirds of industrial petroleum is used for material feedstocks. But two-thirds of petroleum is used for transportation, and transportation petroleum use has increased at 2% per year from 1993 to 2006.

The United States must now import two-thirds of its petroleum needs, and that proportion is increasing as consumption rises and production declines. Figure 1.15 tracks the proportions of U.S. oil consumption met by domestic sources and by imports. In 1973, the country supplied 63% of its needs and imported less than 37%; now the United States supplies only 34% of its needs and imports 66%.

The United States imports oil from several exporting countries, headed by Canada (16% in 2005), Mexico (13%), Saudi Arabia (11%), and Venezuela (11%). Total imports in 2006 were 13.6 million barrels per day, of which 40% came from OPEC (Organization of Petroleum Exporting Countries) and 60% from non-OPEC countries. Of OPEC imports, 40% (or 16% of total imports) came from the Persian Gulf, mostly Saudi Arabia and Iraq.

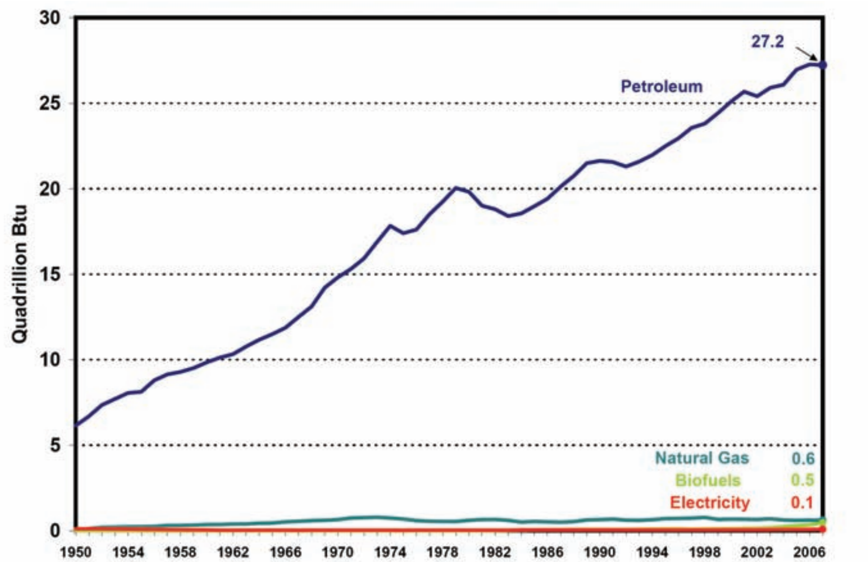
An increasing proportion of future imports will come from the Persian Gulf. This area is home to the vast majority of the world's remaining oil reserves, and continues to be one of the most politically unstable parts of the world.

1.5 Summary

Human-developed science and technology have enabled the conversion of energy sources for productive uses. Through history, the resulting energy use has spurred advancement of human society and civilization. Energy has freed people from slave and animal labor, from agrarian society, and from the constraints of space. It has triggered the development of industry and communications. Only since the mid-nineteenth century and the advance of fossil fuels has energy use enabled unprecedented fourfold growth of human population and a fortyfold increase in the global economy.

But our patterns of energy production and use are not sustainable. World energy use continues to grow rapidly, and 86% comes from carbon-emitting fossil fuels. Petroleum is our largest source and its reserves are concentrated in the politically volatile Persian Gulf. With 20% of the world's population consuming 75% of the world energy and controlling

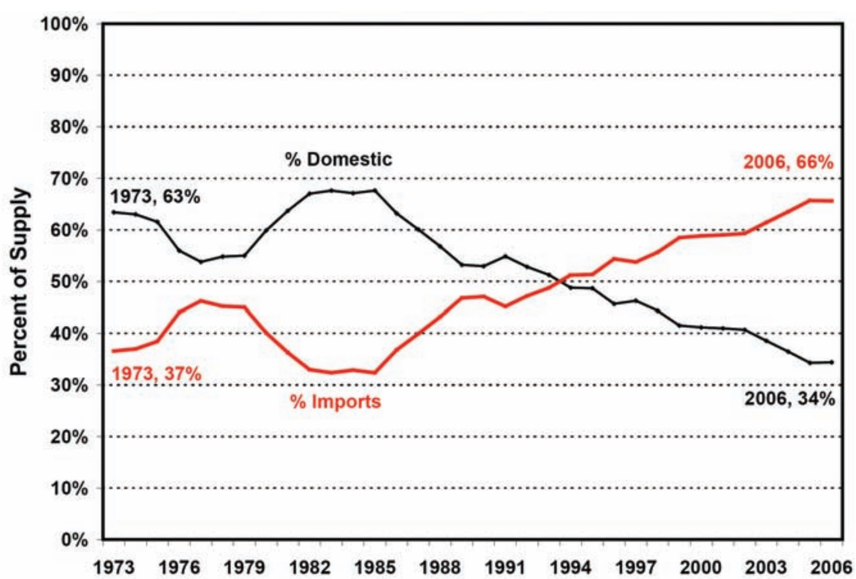
figure 1.14 U.S. Transportation Energy, 1950–2006



Although petroleum use in other sectors has declined, growth is dramatic in the transportation sector. Thus, oil is still our number-one energy source, contributing 40% of total energy consumption.

Source: data from U.S. EIA, 2007a, 2007c

figure 1.15 U.S. Petroleum Supply from Domestic Production and Imports, 1973–2006



Source: U.S. EIA, 2007a, 2007c

90% of the global economy, while the poorest 80% struggle toward development, we are a long way from an equitable energy and economic system.

The U.S. energy patterns are similar: 86% of energy consumed is fossil fuels. Growth has averaged about 1.2% from 1969 to 2005. During that time, however, the good news is that the United States has increased the economy of energy use with declining energy intensity (energy/$GDP) and stable energy per capita. However, electricity use has increased, and 92% of it is generated by steam power that is inherently inefficient. The United States has increased dependence on imported oil, due to rising consumption and declining domestic production. In 2006, the United States imported 66% of its oil consumption needs, up from 37% in 1973. That trend continues upward as domestic oil production continues to decline and petroleum use for transportation continues to increase at more than 2% per year.

1.5.1 Sustainable Energy: Improve Efficiency, Replace Oil, Reduce Carbon

We simplified our energy problem as three primary issues: oil, carbon, and growing demand. We can also characterize the solutions to our energy problem in three primary objectives or ends and three means to those ends. We need to

1. *Improve efficiency* of energy use to reduce demand growth. We have made progress in improving the efficiency and economic effectiveness of our energy use, but significant opportunities remain.
2. *Replace oil* with other sources to avoid economic and security consequences of oil dependence. We believe that our best immediate opportunities are biofuels and electricity.
3. *Increase carbon-free energy sources,* reduce fossil fuel use, and sequester carbon emissions. We believe that renewable energy sources, including solar, wind, and biomass, offer our best opportunity for carbon-free energy. There is also strong interest in reviving the nuclear industry and in clean coal technology with carbon sequestration, but they face economic, technical, security, and environmental uncertainties.

We can achieve these objectives through three diverse means, all of which are needed for rapid energy market transformation to improve efficiency, replace oil, and increase carbon-free sources:

- Advanced *sustainable energy technologies,* including efficient production and use, renewable energy systems, and selected clean and safe fossil fuel and nuclear technologies.
- *Consumer and community choice* for investment in efficiency and sustainable technologies, and conservation through modifying practices and behavior. Consumer and community choice for sustainable energy is driven by economic, environmental, social, health, security, and other factors, and can take the form of a social movement.
- *Public policies* to develop and deploy technologies and enhance consumer and community choice through investments, incentives, and regulations. Policies can originate in

international agreements and federal, state, and local government market transformation programs.

The remainder of this book explores the constraints and opportunities we face in achieving sustainable energy. It focuses on the three objectives and three means listed above. The book is organized around three dominating energy consuming sectors in Sections III, IV, and V:

- *Buildings* consume nearly half of our energy use, including operating heating, cooling, and electrical appliances and the embodied energy of materials and construction. They contribute 40% of carbon dioxide (CO_2) emissions, the main cause of global climate change. We have made improvements in building energy efficiency, but significant opportunities remain.
- *Electricity* used in buildings and industry requires 40% of our energy consumption and it is growing. More than half of electricity generation comes from coal, one-fifth from nuclear, one-sixth from natural gas, and one-eighth from renewable energy. Electricity generation causes 39% of U.S. carbon dioxide emissions. Wind and solar photovoltaic power have the fastest percentage rates of growth of all sources of electricity.
- *Transportation* uses two-thirds of our oil consumption, and it is 96% dependent on oil. Transportation energy depends on vehicle efficiency, vehicle miles traveled, modal (e.g., car, transit, walking) availability and choice, land use patterns, and the price of fuel. Sustainable transportation must address all of these factors as well as alternative fuels, such as biofuels and electricity.

Before addressing these sectors and energy policy in Section VI of the book, this Section I continues with an introduction to energy sources and constraints in Chapter 2, and different visions of our energy future in Chapter 3. Section II introduces fundamentals of energy science and life-cycle analysis.

CHAPTER 2

Energy Sources and Sustainability

This chapter discusses some of the important life-cycle concerns of our current patterns of energy production and use. Our continued dependence on oil as the largest energy source for our economy poses special geologic, geographic, and political problems. The supply is limited by geologic conditions. And what geologic supply remains is concentrated in the politically unstable Middle East. We have already experienced not only the price shocks associated with a cartel-influenced production market, but also the political and military implications of access to a precious resource.

Just how much of this resource remains is the subject of continuing debate, the so-called "peak oil" debate, centering on the ultimately available quantity of conventional crude oil and when global production will peak. If the world economy remains highly dependent on growing oil demand when that peak occurs, there will be severe economic and political repercussions.

After examining the state of our oil resource and other fossil fuel supplies, this chapter reviews environmental implications of fossil fuel energy sources. It focuses on global climate change, which is triggered in large part by carbon-based fossil fuel combustion and the resulting carbon dioxide emissions. We study the scientific consensus on the topic, and also review other environmental impacts of fossil energy, such as urban air pollution.

Finally, we evaluate our progress in developing non–carbon-based energy sources, including nuclear power and renewable energy, as well as improvements in energy efficiency. Once thought of as the major future source of energy, nuclear power stagnated in the past two decades and amounts to only about 8% of U.S. and 6% of global energy. Recent calls for a renaissance of nuclear power must still confront barriers of public life-cycle concerns over safety and security, long-term waste management, and nuclear weapons proliferation. The implication is that we must continue to look for alternatives.

Efficiency and renewable sources have been viewed with great hope, and indeed best fit the criteria for sustainable energy. However, significant opportunities for efficiency improvements remain untapped and renewable sources still contribute only a small proportion of commercial energy. Still, efficiency is the most cost-effective and environmentally beneficial of energy options; renewable wind and solar electric and biofuels are growing at the fastest rate of all energy sources today; they provide the greatest promise for sustainable energy. These options are introduced in this chapter and are emphasized in the remainder of the book.

Before we dive into the topics of peak oil, climate change, and non-carbon energy in the context of sustainability, it is important to understand that context and introduce some criteria for sustainable energy.

2.1 Criteria for Sustainable Energy

Before reviewing the implications of energy options, it is necessary to discuss further what we mean by sustainable energy. In Chapter 1 we defined sustainability and sustainable energy:

> **Sustainability:** patterns of economic, environmental, and social progress that meet the needs of the present day without reducing the capacity to meet future needs.
> **Sustainable energy:** patterns of energy production and use that can support society's present and future needs with the least life-cycle economic, environmental, and social costs and consequences.

Both definitions emphasize two important criteria:

1. *A broad range of considerations:* Sustainable energy goes beyond short-term economic effects to consider environmental, social, security, and long-term economic implications of energy choices.
2. *The future:* Sustainable energy by definition aims to sustain the availability of energy to meet the needs of future generations. To be sustainable, our actions and choices should neither preclude options nor place undue economic and environmental burdens on those who follow us.

Human history tells us that our predecessors did not think too much about the future, but simply muddled through, doing the best they could and believing that the future took care of itself. Despite calamities, resource shortages, famine, and war, civilization advanced, and here we are.

Many people today think like our predecessors: the future will take care of itself. These "present-thinkers" believe someone will find more oil or discover alternatives. Through technology, they think someone will figure out how to get better at reducing impacts of energy use; at converting coal to energy cleanly; at developing renewable energy and safe nuclear power; at using energy more efficiently. They say, "I'll worry about me and mine, and the greater economic and social system will take care of the rest. That's the way it has always been."

Others think differently. They look at the world around them and see challenges and opportunities. The challenges are inequities and injustices; tensions between security and liberty; local, regional, and global environmental impacts of human activity; and a very uncertain future, among others. The opportunities come from their realization that, unlike our predecessors, we have the power to determine our destiny, to take care of the future ourselves. That power comes from increasing economic wealth, growing democratization, global communication networks, and people's expanding awareness of the world and the future, and their capacity to shape them.

These "future-thinkers" do not see future energy taking care of itself. Today is the future from the perspective of the 1973 oil crisis, and despite great attention by the "greater economic and social system," little has changed in the world's patterns of energy use. Future-thinkers realize that these patterns are not sustainable and that we do not have the luxury of time to wait until that system takes care of the future.

They argue that we need to act quickly, decisively, and collectively to develop more sustainable patterns of energy production and use. The first step to recognizing the need for change is to recognize the problem. This chapter investigates the major constraints to sustainability posed by our current energy patterns.

But how do we make personal, community, and societal choices for more sustainable energy? Given the criteria above, there are several factors to consider:

- Renewability or abundance of the energy resource for long-term reliability
- Life-cycle economic benefits and costs, including cost-effectiveness and national and local economy effects
- Life-cycle environmental benefits and costs, including local, regional, and global effects
- Life-cycle social benefits and costs, including effects on human health, communities, equity, and the disadvantaged
- Life-cycle security benefits and costs, including energy, environmental, and national effects
- Uncertainties of life-cycle benefits and costs

Life-cycle analysis is fundamental to sustainability because it aims to capture full costs and consequences over a long time horizon. We will see in Chapter 5 that life-cycle analysis involves specific techniques, such as net energy analysis and economic and environmental assessment, and a general capacity to think broadly and long-term. For example,

- Life-cycle analysis involves not just considering the carbon emissions from a coal-burning power plant but the full range of economic, environmental, and social costs and benefits of coal mining, processing, and transport; power-plant operations; and waste ash disposal.
- It involves not just the cost effectiveness of a solar photovoltaic array, but the costs and benefits of materials acquisition, production processes, and waste disposal in its production.
- It involves not only the production cost of ethanol from corn or cellulose, but also the energy, fertilizer, irrigation water, and runoff pollution required to produce it; the

carbon and other air emissions from its production and use; the effect on corn and food prices; and other inputs and outputs.

- It includes not only the construction and operating costs and electricity sales revenues from a nuclear power plant, but the full nuclear fuel cycle, from mining to processing to plant operations to long-term waste storage; plant security and safety considerations; ultimate plant decommissioning; and nuclear weapon proliferation concerns.

2.2 The Geologic Limits of Fossil Fuels

Petroleum is a nonrenewable, finite resource subject to depletion. Yet the United States and world economies are dependent on petroleum, which supplies 40% and 37% of their energy, respectively. The big question is: What is the ultimate quantity of this finite resource? A serious scientific debate is raging about when oil production will peak and begin to decline. If it peaks before our economy is able to wean itself from oil, the repercussions will be devastating. Even if that peak is delayed, future supplies of oil will need to come increasingly from the politically volatile Persian Gulf region where the majority of the remaining petroleum resides.

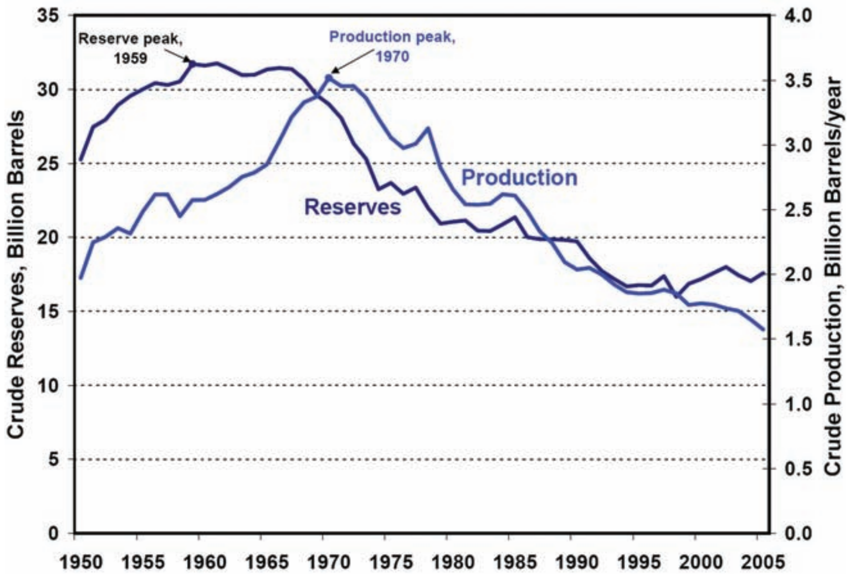
2.2.1 The Peak Oil Debate

For decades, economists and geologists have debated an obscure theory of a former Shell Oil and U.S. Geological Survey geophysicist M. King Hubbert, who, in the mid-1950s, accurately predicted that U.S. domestic oil production would peak in 1970 and decline thereafter, never to rise to that peak again (Figure 2.1). Hubbert also predicted world oil would peak about the year 2000 (Figure 2.2). He died in 1989, but his legacy lives on in a contemporary debate over his theory, its validity, and its implications.

Hubbert's basic theory is that because oil is nonrenewable, under consistent geologic, economic, and market conditions, its production will rise to a peak then fall predictably in a bell curve (Figure 2.2). The peak in production will occur sometime after a peak in the "reserves" of the resource. As shown in Figure 2.1 this lag time was eleven years for the United States. The area under the production bell curve is the **ultimate recoverable quantity** of the resource, or what Hubbert called Q_∞. This turns out to be a critical factor in understanding our energy supply situation, so we need to look at it more closely.

Reserves are the quantity of known deposits that are economically recoverable at today's prices. They are often divided into *proven* and *probable* reserves. Reserves are not static but are depleted by production and added to by new discoveries and by new technologies and higher prices that make deposits once too expensive to extract, profitable to recover (see Figure 2.3). Two prominent industry journals, *Oil & Gas Journal* (*O & GJ*) and *World Oil*, survey companies and governments annually and provide self-reported estimates of oil and natural gas reserves by country, region, and the world as a whole. As shown in Figure 2.3, oil reserves are estimated at 1082 billion barrels (Bbbls) by *World Oil*. The *O & GJ* 2007 estimate of

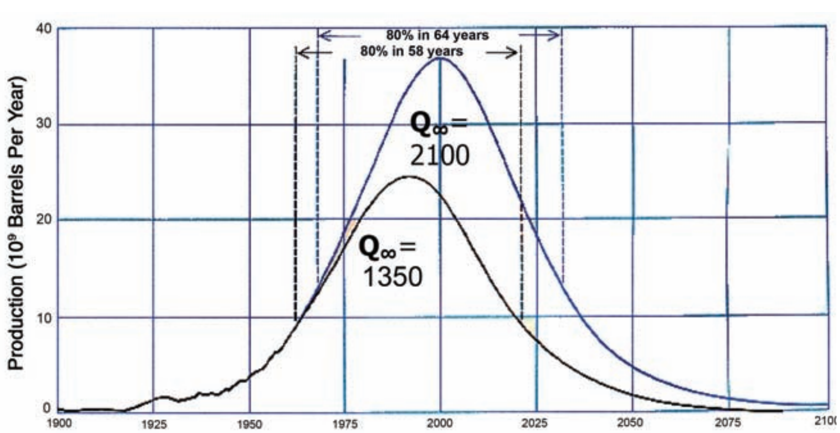
figure 2.1 **Oil Production Peak for the Continental United States**



The peak in 1970 followed the peak in reserves by eleven years. In 1960, Hubbert accurately predicted the 1970 peak in production based on the reserve peak.

Source: data from U.S. EIA, 2006a

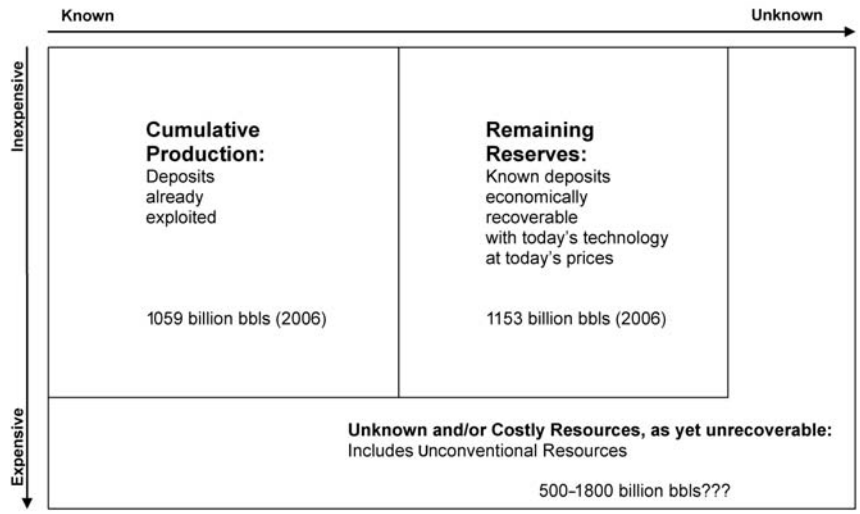
figure 2.2 **Theoretical Production Curve for World Oil**



As early as 1949, Hubbert predicted the world oil production peak in 2000 (blue curve) based on 2100 billion barrels ultimate recoverable quantity of the resource (Q_∞) and symmetrical rise and fall of production.

Source: adapted from Hubbert, 1971

figure 2.3 **Ultimate Recoverable Quantity (*Q*) of a Nonrenewable Resource**



Q_∞ is made up of cumulative production to-date, reserves (known and economically recoverable at today's prices), and additional resources that ultimately will be found or made recoverable by new technology or higher prices.

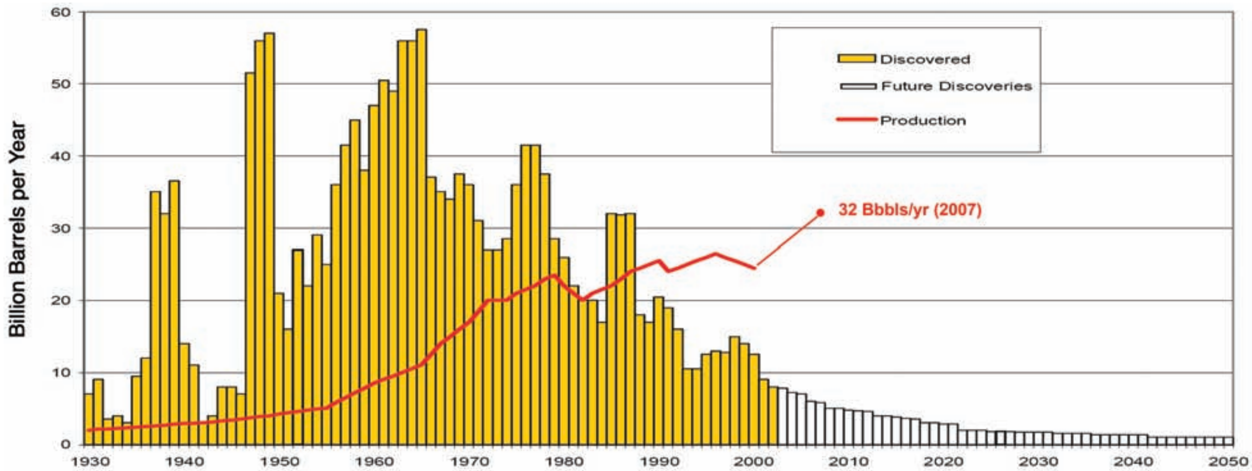
1317 Bbbls includes 174 Bbbls of unconventional oil from oil sands in Canada, a quantity many believe is too difficult to put into production to be considered a reserve.

Reserves are an important measure of today's available deposits, but they do not indicate the ultimate available resource. Figure 2.3 shows that the ultimate available, or the Q_∞ area under Hubbert's curve is made up of (a) current proven reserves (1153 Bbbls in 2007); plus (b) cumulative production to-date (1059 Bbbls through 2006, growing at 32 Bbbls per year in 2007); plus (c) unknown, probable, or not-yet-recoverable deposits that will become future reserves. This latter amount is the most speculative and the primary subject of the peak-oil debate, because it determines how much oil will be recovered and thus when the peak will occur for a given demand. Hubbert's graph given as Figure 2.2 shows the world peak for two different values of Q_∞. The value of 2100 Bbbls gives a peak at the year 2000.

So what is our current best estimate of Q_∞? It depends on whom you ask. In the most definitive government study of oil and natural gas resources to-date, the U.S. Geological Survey (USGS, 2000) provided three estimates: a low estimate of 2248 Bbbls (with 95% confidence), a high estimate of 3896 Bbbls (with 5% confidence), and a mean estimate of 3003 Bbbls. Other recent estimates are in the 1700 to 2400 Bbbl range or close to the USGS low estimate.

Critics of the USGS higher estimates point out that its higher estimates require a rate of discovery or addition to reserves that far exceeds the trends of the past forty years. Figure 2.4 illustrates this point. Most current production is tapping old discoveries and the decline of new discoveries is expected to continue.

figure 2.4 Growing Disparity between World Oil Production and Oil Discoveries



In 2004, the trade publication *Oil & Gas Journal* lamented the declining oil discovery rate in the face of rising production. The gold bars give actual data; the white bars are projections. The 2007 record demand rate of 32 Bbbls/yr is added.

Source: based on *Oil & Gas Journal* data

The two sides of this debate have several legitimate arguments. On one side are the peak oil proponents or "depletionists" who argue that the peak is imminent. Their critics call them doomdayers. The peak-oil skeptics argue there is no reason to worry. Proponent Colin Campbell groups these critics into two camps:

- The "economists" argue that the self-correcting economic system will solve shortage problems. When the supply of a commodity decreases, its price increases, demand decreases, and there is an economic incentive for finding replacements.
- The "pretenders" understand the situation but pretend otherwise for short-term political or economic objectives. They may include government and industry representatives who stand to gain from the status quo.

These critics of peak oil make the following points:

- World oil reserve additions continue to outpace production. *O & GJ* world reserve estimates increased 2% from January 1, 2006, to January 1, 2007.
- Hubbert's theory may have worked for U.S. oil and other cases (such as Pennsylvania anthracite coal) but it has failed in other applications (e.g., U.S. natural gas). Several depletionists like Campbell have had to revise predictions because their predicted global peak date has passed and production continues to increase.

- Although oil resources are finite, no one knows just how finite. Estimates of Q_∞ generally include conventional but not unconventional sources of oil. Unconventional oil includes potential deep-sea deposits (like Chevron's 2006 find in the Gulf of Mexico estimated at 3 to 15 Bbbls), oil shale (estimated 2000 Bbbls in the United States), heavy oil (in Venezuela), and oil sands (in Canada). *O&GJ*'s inclusion of 175 Bbbls of Canadian oil sands in reserves in 2002 indicates that they are at least close to being profitable. Oil sands production in 2007 is 1.3 Mbbls/day or about 0.45 Bbbls per year about 1.3% of world oil production, with expectations to double that by 2015.
- Depletionists argue that Hubbert offers a simple and elegant theory, but the real world is not so simple. Experience has shown that world oil production does not fit the "consistent geologic, economic, and market conditions" that Hubbert's bell shape curve assumes. Indeed, political motivations and market capture by OPEC countries have manipulated the market patterns of oil production and consumption. Instead of rising uniformly after the 1973 oil crisis, production has gone up and down (see Figure 2.4).
- The depletionists are alarmists following a long line of prophets of doom, who have been proven wrong time and time again.

However, the peak-oil proponents argue that Hubbert's theory is not only simple and intuitive, but it has proven itself in several regional studies, such as in the cases of the continental United States (given in Figure 2.1), Alaska, the North Sea, and Russia, among others.

The proponents say that current estimates of reserves do seem to indicate a fairly strong resource base, but closer inspection reveals they are at best uncertain and at worst, wrong. They are self-reported by companies and countries with self-interest for over-reporting. Oil companies' stock values are closely tied to their assets (reserves). In 2004, Shell Oil reevaluated its oil reserves and reduced the estimates by 20%. In internal company memos, the chief of the exploration division said he was "sick and tired of lying about the extent of our reserves." Shell's CEO resigned in disgrace, and its stock dropped 12%.

Similarly, for countries in OPEC, production quotas are linked to their reserves—the more they estimate, the greater their production quota, and the more income they receive. When these rules were established in 1987, the combined reserves of six OPEC countries mysteriously and suspiciously jumped by 300 Bbbls (35% of global reserves at the time) without any major discovery of new fields.

Peak-oil proponents argue that even if Q_∞ is higher than expected (say 3500 Bbbls instead of 2500 Bbbls with the addition of unconventional deposits), the peak will be extended by only a few years as shown in Figure 2.2. Unconventional sources for oil will provide some additions to reserves, but for thirty years they have continued to be out of reach for economic and environmental reasons. When *O & GJ* added Canada's oil sands to reserves in 2002, analysts thought the biggest barriers to development were low oil prices (oil was then $25/bbl) and government environmental regulations. However, by 2007, even with oil approaching $100/bbl, production has just exceeded 1 million barrels per day despite capital investment approaching $50 billion since 2000. Referred to by MIT's *Technology Review* as "dirty oil," extracting bitumen from the sands is an energy-intensive process with far more carbon dioxide emissions and environmental impacts than conventional oil (Bourzac, 2005). Other nonconventional oil sources are likely to encounter similar constraints.

Finally, these proponents argue that even if the peak is uncertain, taking action now will have benefits. We have done very little to arrest our economy's dependence on oil in the years since our first wake-up call in the oil crisis of the 1970s. Reducing our dependence on oil today can postpone the peak, give us more time to transition to other sources, and begin to relieve the environmental and security impacts of our oil dependency.

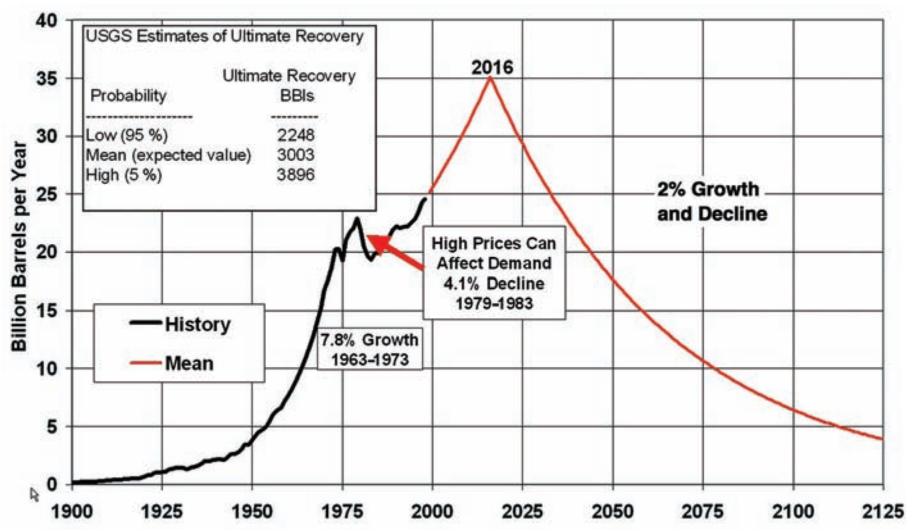
Both critics and proponents of peak oil agree that this is a serious issue that should be the subject of additional study, that industry and government action should be based on the best available information, and that aggregate reserve data are flawed and a better system of data gathering and verification is needed.

In addition, both sides agree that demand in developing countries will likely push up global demand. World oil production was stagnant from 1977 to 1993, but since then demand for oil has risen by 1.4% per year to 2003 and 4% in 2004 and 2005. Despite a smaller increase in 2006 due to higher prices, demand will likely continue to push oil markets and production capabilities as consumption expands in the less developed countries led by China and India. Still, they disagree about the implications of that growth because they contend different values of Q_∞.

The USGS 2000 study offers relatively optimistic estimates of Q_∞ ranging from 2248 to 3896 Bbbls. U.S. EIA analysis shows that even with these optimistic estimates a production peak may not be far away. The EIA graph in Figure 2.5 assumes the USGS mean estimate (3003 Bbbls), a constant 2% per year production increase to a sharp peak in the year 2016, followed by a 2% per year decline. EIA also ran this analysis with all three USGS estimates of Q_∞ and different production growth rates to peak and a sharp decline at a rate of "R/P" equal to 10. The date of peak varied considerably with different growth rates from 2016 to 2050, but for each growth rate, using the much higher estimate of 3896 Bbbl extended the peak only about 10 years compared to the mean estimate of 3003 Bbbl. We will see in the next chapter that EIA has not considered this analysis in making its energy projections to 2030.

The term **R/P** is Reserves (bbls) over annual Production (bbls/yr) and is called the **static reserve index.** It is an important factor, as it tells us the number of years the current reserves would last if they were produced at current production rates. For example, the U.S. oil reserves in 2006 would last just 11 years if they were produced at the 2006 rate of production. But of course, both current reserves and current production are not static but change each year, so R/P does not give the lifetime of the reserves (as some people assume). However, it is still a good measure of the relative strength of the reserve base. Usually an R/P index of 15 or less indicates a weak reserve base and declining production. Table 2.1 gives 2006 reserves, production, and R/P for selected countries and the world.

Actual world production has not shown a peak, but some countries have, even though they have not followed a nice bell curve. Figure 2.6 shows actual world oil production from 1973 to 2006 and breaks out non-OPEC, OPEC, and Persian Gulf production. Figure 2.7 shows production from selected countries. After readjusting to its new economy, Russia's figure 2.5 **Future World Oil Production**



U.S. EIA study reports 2016 peak based on USGS mean Q_∞ (3003 Bbbls) and 2% growth to sharp peak and subsequent 2% decline.

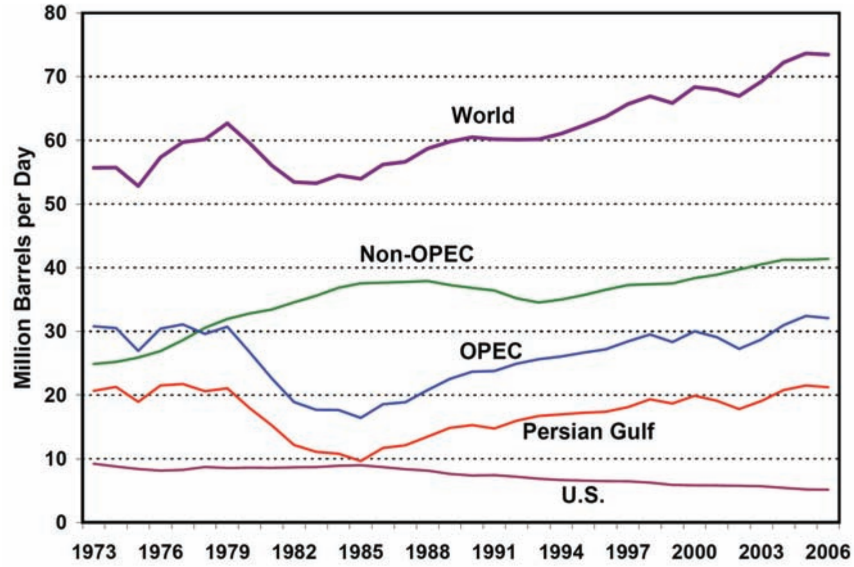
Source: U.S. EIA, 2003

table 2.1 **Oil Reserves (2007), Production (2006), and R/P for Selected Countries and the World**

Country	2007 Reserves (R) Bbbl/yr	2006 Production (P) Bbbl/yr	Static Reserve Index R/P Years
Saudi Arabia**	260	3.28	79
Iran**	136	1.41	96
Iraq**	115	0.70	164
Kuwait**	99	0.80	112
UAE**	96	0.93	103
Venezuela*	80	0.94	85
Russia	60	3.46	17
Nigeria*	36	0.81	39
China	24	1.35	18
United States	22	1.87	11
Mexico	12	1.19	10
Norway	8	0.90	9
Canada	5 (+175 o.s.†)	0.91	5 (198)
United Kingdom	4	0.54	7
World Total	**1142 (+175 o.s.)**	**26.5**	**43 (50)**

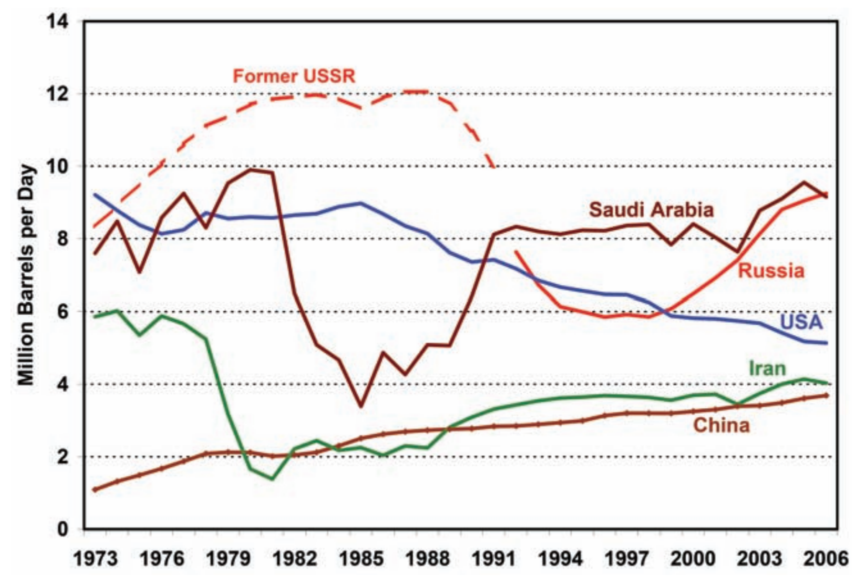
* Members of OPEC not in Persian Gulf. Other members include Libya, Algeria, and Indonesia.
** Members of OPEC in Persian Gulf.
† o.s. = oil sands
Source: data from U.S. EIA, 2007d, and *Oil & Gas Journal,* 2006

figure 2.6 World Oil Production, Various Regions, 1973–2006



Source: data from U.S. EIA, 2007a

figure 2.7 Oil Production in Selected Countries, 1973–2006



Russia overcame Saudi Arabia as largest producer in 2006.

Source: data from U.S. EIA, 2007a

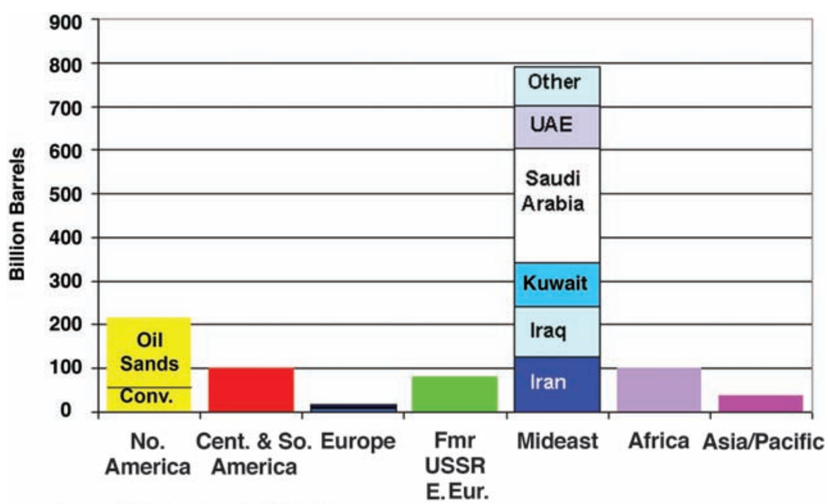
production has grown and exceeded Saudi Arabia's in 2006. Despite Russia's production increase, non-OPEC production growth is slowing as production in the United States, Mexico, and Norway's and U.K.'s North Sea fields, continued to decline in 2006. Future production increases will come from OPEC and the Persian Gulf where reserves are concentrated. Despite prices pushing $100/bbl, world oil production continued to expand in 2007, growing at 1.7% per year to 88 Mbbl/da or an equivalent annual production of 32 Bbbl/yr.

2.2.2 U.S. Oil Depletion and Dependency

Although there are uncertainties about when world oil production will peak, we know for certain that U.S. oil production peaked in 1970 (Figures 1.13, 2.1, and 2.7), and as a result we are increasingly dependent on foreign sources. We now import two-thirds of the oil we consume (Figure 1.15) and that percentage continues to grow as consumption increases and production declines.

In 2006, 40% of U.S. oil imports came from OPEC members and only 16% of that came from Persian Gulf OPEC members (Saudi Arabia, Iraq, Iran, Kuwait, and UAE), but that is likely to change. As shown in Table 2.1 and Figure 2.8, non-OPEC exporters, with the exception of Russia, have very limited reserves, and three-fourths of global reserves are in OPEC countries. Two-thirds of this OPEC oil is located in Persian Gulf countries, causing the rest of the world to become increasingly dependent on the Persian Gulf. By late 2004,

figure 2.8 **World Oil Reserves by Region, 2005**



The Mideast dominates reserves. Canadian oil sands account for 70% of North American reserves.

Source: adapted from U.S. EIA, 2005; based on *Oil & Gas Journal* data oil imports accounted for one-third of the U.S. trade deficit, a continuing trend influencing the declining value of the dollar. World oil prices hit a record \$96/bbl at this writing in November 2007.

It is ironic that the countries with the greatest oil wealth are among the world's most politically unstable; fast wealth seems to breed corruption, inequity, and repression. Amory Lovins, et al. (2004, p. 18), write "only 9% of the world oil reserves are held by countries considered 'free' by Freedom House, and oil riches correlate well with Transparency International's corruption ratings."

Because access to oil is vital for the future U.S. and global economy, it is no surprise that the Persian Gulf region has attracted so much political attention. Lovins, et al. (2004), argue that "reliance on unstable oil sources incurs costs for both buying it and defending it," and estimate that the continuing cost of military security in the Middle East to protect access to oil is the equivalent of \$25/bbl of oil we import. Regarding the Gulf War and the Iraqi War, they speculate:

> Historians will long debate whether the United States would have sent a half-million troops to liberate Kuwait in 1991 if Kuwait just grew broccoli and the United States didn't need it. Decades hence, historians may be better able to say whether an odious tyrant would have been overthrown with such alacrity in 2003 if he didn't control the world's second-largest oil reserves. (Lovins, et al., 2004, pp. 17, 19)

2.2.3 Natural Gas and Coal

As nonrenewable resources, natural gas and coal are ultimately subject to the same supply constraints as petroleum. However, due to lower U.S. and global demand for these fuels, and greater abundance of coal, the potential supply effects are neither as severe nor as immediate. Table 2.2 gives the natural gas reserves and production rates of the same selected countries shown in Table 2.1. Russia has the greatest reserves and the United States is fourth with 204 trillion cubic feet (Tcf), although the U.S. R/P is only 11.

Ultimately, natural gas (NG) resources are estimated to be as large as oil on an energy equivalent basis. The USGS (2000) estimates the exploitable NG resources (Q_∞) at 15,400 Tcf (mean value), of which about 2800 Tcf have been used and 6200 Tcf are listed as reserves. Thus, USGS estimates that about one-sixth of Q_∞ NG has been used, compared to one-third for Q_∞ oil. World NG production has increased by 2.1% per year since 1992, compared to 1.2% for oil. Peak-oil proponent Jean Laherrere estimates ultimate NG resources at 10,000 Tcf; 12,000 if unconventional gas is included. Natural gas thus has more room to grow, but will be subject to the same peak production as oil; however, the NG peak is likely to be a few decades later than oil's peak.

The current U.S. net imports of NG are about 16% of consumption (compared to 4% in 1986). They are mostly by pipeline from Canada. However, like the United States, Canada's reserve base is limited and the United States will need to rely on other sources of imported natural gas to fuel its expected growing demand. According to U.S. EIA projections, future

table 2.2 Natural Gas Reserves (2007), Production (2004), and R/P for Selected Countries and the World

Country	2007 Reserves (R) Tcf/yr	2004 Production (P) Tcf/yr	Static Reserve Index R/P Years
Russia	1680	21.0	75
Iran**	974	2.7	328
Saudi Arabia**	240	2.0	103
United States	204	19.0	11
UAE**	203	1.5	124
Nigeria*	182	0.5	236
Venezuela*	152	1.1	158
Iraq**	112	0.1	1812
Norway	82	2.4	28
China	80	1.2	56
Canada	58	6.6	9
Kuwait**	55	0.3	160
United Kingdom	17	3.6	5
Mexico	15	1.3	10
World Total	**6183**	**98.6**	**63**

* Members of OPEC not in Persian Gulf. Other members include Libya, Algeria, and Indonesia.
** Members of OPEC in Persian Gulf.
SOURCE: data from U.S. EIA, 2006b, and *Oil & Gas Journal,* 2006

imports are expected to increase from liquefied natural gas (LNG) imports to 21% or 5 Tcf by 2025. To put this in perspective, Japan is currently the world's largest LNG importer with 9 Tcf.

Whereas Saudi Arabia has 23% of the world's oil reserves and Russia has 27% of the natural gas reserves, the United States has 27%, or 267 billion short tons (Bt), of the world's coal reserves (997 Bt). The United States produces 18% of the world's coal annually (1.1 billion tons [Bt] giving an R/P = 236 years), about half of China's production that has doubled in the past fifteen years. Although coal is far more plentiful than oil and natural gas (the world coal R/P is 180 years), its solid form complicates its extraction, transport, and use, which limits its applications. More importantly, it has greater carbon content and more impurities than oil and gas, and thus produces more carbon dioxide and air pollution when burned. We have technologies to mitigate some of these effects and more are under development, but as discussed in the next section, these environmental constraints on coal are its greatest limiting factor.

2.3 The Environmental Limits of Fossil Fuels

Energy fuels our economy and quality of life, but it is costly both in monetary terms and in impacts to the natural and human environment. These impacts are part of the "cost of doing business" but to a large extent they are not included in the costs of energy. They are termed externalities. **Externalities** are social costs borne by users and non-users alike, but not internally by the producer and thus are not reflected in the price of goods or services produced. To achieve sustainable energy, we must consider these costs over the fuel or system's life cycle.

These environmental impacts include air pollution from the combustion of fossil fuels, radioactive materials involved in the nuclear fuel cycle, impacts on lands and waters of fuel extraction, and transport and construction of conversion systems. Before addressing these impacts, the section below discusses what appears to be the major environmental constraint facing fossil energy—global climate change triggered by greenhouse gas emissions, primarily carbon dioxide from fossil fuel combustion.

2.3.1 Climate Change

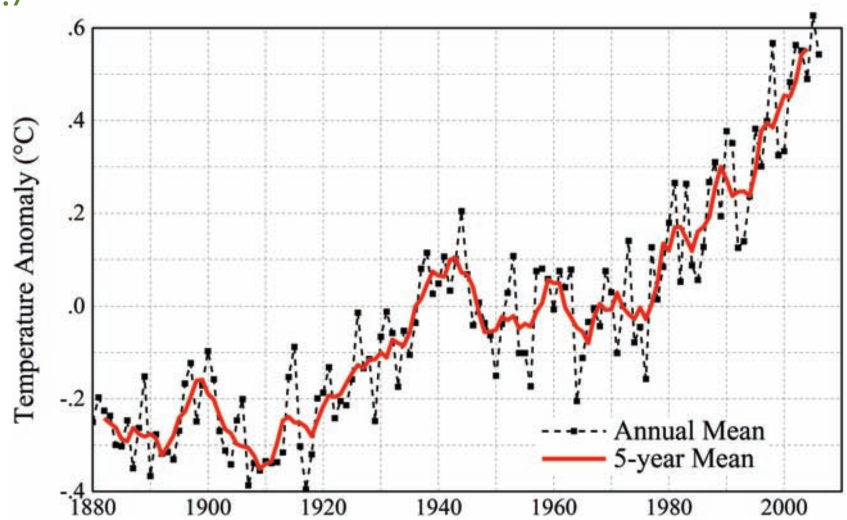
For decades, scientists studying the Earth's energy balance have understood that incoming solar radiation and the Earth's outgoing back-radiation to space are regulated by the atmosphere. A number of atmospheric gases, principally carbon dioxide (CO_2) and water vapor, transmit most of the short solar wavelengths but absorb most of the longer wavelengths of the Earth's back-radiation, holding in energy and warming the Earth's atmosphere and surface—much like the glass in a greenhouse (see Section 4.6.3, Figure 4.8).

Thirty years ago this was a theory. But in the past decade, global warming is now a household term, deemed one of the most difficult problems facing society in the new century. Increasingly sophisticated monitoring has bolstered the theory and revealed disturbing trends:

a. Rising global emissions of CO_2 and other so-called greenhouse gases (GHG), including methane, chlorofluorocarbons (CFCs), and nitrogen oxides
b. Rising global concentrations of CO_2
c. Rising global mean temperature
d. Retreating polar ice caps due to higher temperatures

The most obvious trend is the increase in average temperature. Figure 2.9 shows annual mean temperature from 1880 to 2006. The temperature scale is relative to the base period 1951–1980. The figure shows that global temperature has warmed considerably since 1975. The year 2005 was the warmest year on record, 0.62°C above the 1951–1980 mean. Including 2006, the thirteen warmest years since records began in 1880 have occurred in the past seventeen years since 1990. Data through September indicates that 2007 will be added to this list, rivaling 1998 and 2005 as the hottest.

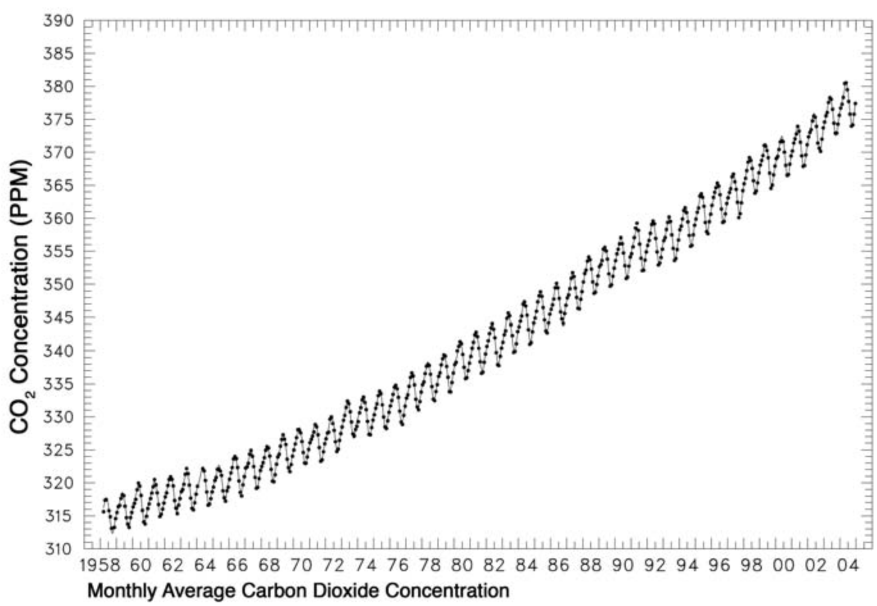
Figure 2.10 gives trends in the concentration of atmospheric carbon dioxide as measured at the Mauna Loa, Hawaii, site between 1958 and 2004. Preindustrial atmospheric CO_2 concentration (1850) is estimated to have been about 280 parts per million (ppm); ice cores from Greenland have shown that this concentration was fairly constant for the previous figure 2.9 **Annual Surface Temperature, 1880–2006 (relative to 1951–1980 mean)**



Note that 2005 was the warmest on record and that the thirteen warmest years since 1880 have occurred in the past seventeen years since 1990.

Source: NASA, 2007

figure 2.10 **Atmospheric CO_2 Concentrations, Mauna Loa Observatory, Hawaii, 1958–2004**



Preindustrial concentrations estimated at 280 ppm (1850) increased to 316 ppm by 1959 and to 377.4 ppm by 2004. This growth continues to 384 ppm in 2007.

Source: Keeling and Whorf, 2005

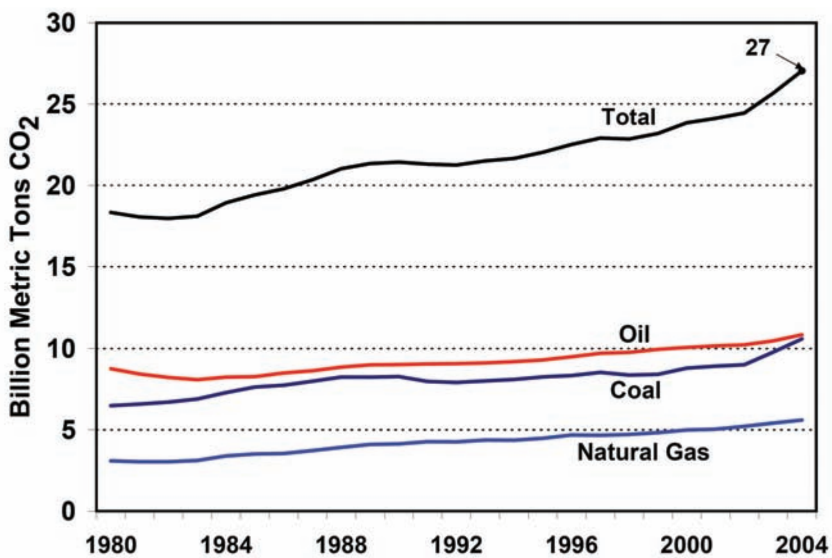
14,000 years. Mauna Loa readings showed a concentration of 316 ppm in 1959 and a 21.5% increase to 377.4 ppm in 2004. In September 2007 Mauna Loa data showed 384 ppm. From 2001 to 2007, atmospheric CO_2 concentration has risen an average 2.1% per year, a doubling rate of thirty-three years.

Figure 2.11 gives global emissions of carbon from combustion of fossil fuels from 1980 to 2004. Global CO_2 emissions increased by one-third between 1983 and 2004 to 27 billion metric tons (Bmt). Oil in transportation is the largest source followed closely by coal power plants; by the year 2010, coal is expected to exceed oil. Emissions have come mostly from the developed countries, but the significant future increases shown in Figure 2.11 are expected mostly from China and India and other parts of the developing world. Figure 2.12 shows U.S. CO_2 emissions, which hit 6 Bmt in 2005, 22% of the world total. Transportation is shown as the largest source, but buildings (combining residential and commercial) are actually larger.

As a result of these actual trends, there has been a strong response from the scientific and political communities to address some fundamental questions.

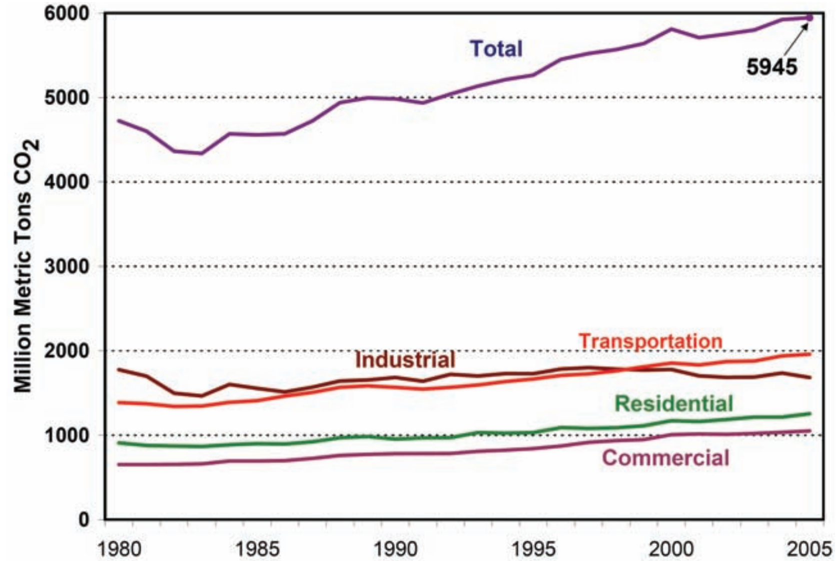
- To what extent is the current trend in global warming due to human emissions of GHG?
- What are the prospects for future emissions and effects on CO_2 concentrations and global temperatures?

figure 2.11 Global CO_2 Emissions by Fuel Type, 1980–2004



Source: data from U.S. EIA, 2006b

figure 2.12 **U.S. CO_2 Emissions by Energy Sector, 1990–2005**



SOURCE: data from U.S. EIA, 2006a

- What are the potential effects of global warming on weather patterns, food production, ecological systems, sea-level rise, and human settlements?
- What actions are warranted by governments, industries, communities, and citizens to respond to potential impacts, control or reduce emissions, or change patterns of energy use?
- How do we compare the uncertainty and risks of future impacts to the cost of reducing those risks?

Not surprisingly, these questions have fueled considerable controversy due to the high stakes and the uncertainty involved.

2.3.1.1 IPCC: Scientific Consensus on Global Warming

The most authoritative scientific body addressing many of these questions is the Intergovernmental Panel on Climate Change (IPCC), established by the United Nations and the World Meteorological Organization in 1988 "to assess on a comprehensive, objective, open, and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation." For its efforts bringing the science of global climate change to the public and political arena, the IPCC shared the 2007 Nobel Peace Prize with Al Gore.

The IPCC is not intended to conduct research but to engage the best science in assessing and interpreting peer-reviewed scientific and technical studies on the subject. IPCC includes four groups: Work Group (WG) I assesses scientific aspects of the climate system and climate change; WG II assesses the consequences of climate change and options for adapting to them; WG III assesses options for limiting GHG emissions and mitigating climate change; the Task Force on National Greenhouse Gas Inventories runs the GHG inventory program.

The IPCC process is a continuous one. Each work group develops a major report over several years. The WG reports undergo extensive review by scientists and governments and serve as the basis for the IPCC assessment reports developed and approved in a plenary conference. Using this process, IPCC has produced four reports, the First Assessment Report (FAR, 1990), the Second Assessment Report (SAR, 1996), the Third Assessment Report (TAR, 2001), and the Fourth Assessment Report (AR4, 2007). The TAR and AR4 included a "Summary for Policymakers." The six-year AR4 effort involved 450 lead authors, 800 contributing authors, and 2500 reviewers from 130 countries.

Succeeding IPCC reports have become more certain about the occurrence of global warming and human influences:

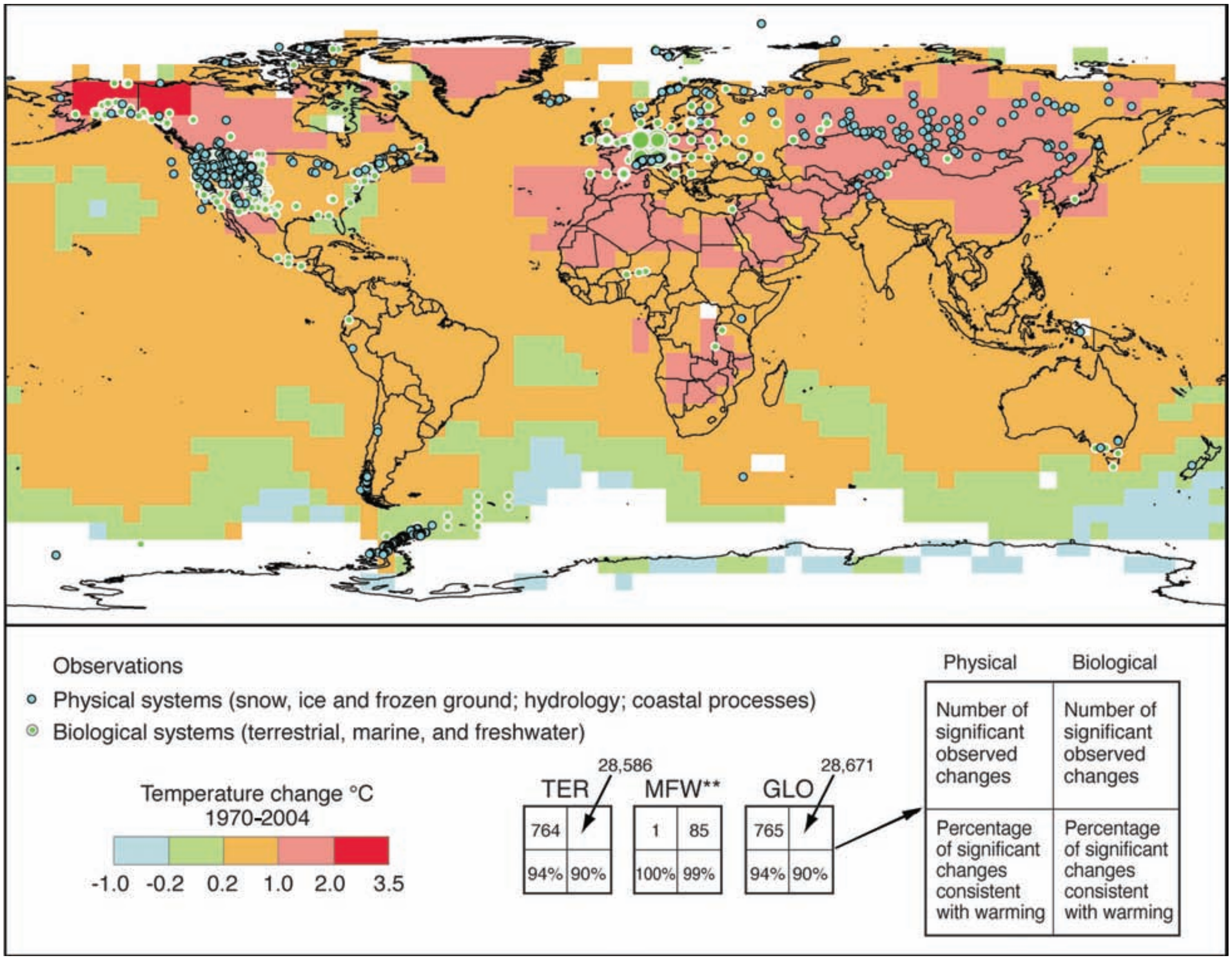
FAR (1990)	"The size of the warming is broadly consistent with predictions of climate models, but the unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more."
SAR (1996)	"The balance of evidence suggests a discernible human influence on climate."
TAR (2001)	"There is new and stronger evidence that most of the warming observed over the last fifty years is attributable to human activities."
AR4 (2007)	"Evidence for warming of the climate system is unequivocal. . . The role of greenhouse gases is well understood and their increases are clearly identified... The net effect of human activities is now quantified and known to cause a warming at the Earth's surface."

Global warming is caused by human activity and its effects are occurring. What sets the 2007 AR4 apart from the previous assessments is (1) the extent of actual observations of climate change and effects; (2) the rising level of certainty that warming is caused by human activity; and (3) the confidence level of predicted impacts. Figure 2.13 from the WG I report shows the extent of change in observations of temperature and physical and biological conditions. The physical and biological observations were taken from 29,000 datasets from 577 studies; 95% of those datasets were from Europe. Nearly all of the observed changes were consistent with the impacts of warming.

The observed effects include the following:

- Increase in glacial melting, the size and number of glacial lakes, and ground instability in permafrost areas and changes in artic/Antarctic ecosystems

figure 2.13 **Surface Temperature Changes, 1970–2004, and Significant Changes in Observations of Physical and Biological Systems**



Observations based on 29,000 datasets from 577 studies, of which 28,000 are from European studies. The two-by-two boxes show the number of datasets with significant changes (top row) and the percent of those consistent with warming (bottom row) for terrestrial (TER), marine and freshwater (MFW), and total global (GLO).

SOURCE: IPCC, 2007

- Increased spring runoff and peak discharge in snow-fed rivers, warming of lakes and rivers
- Earlier timing of spring events, such as leaf-unfolding, bird migration, egg-laying
- Poleward and upward shifts in ranges of plant and animal species

Other observed effects are more difficult to pin directly on global warming because of complicating non-climate factors and adaptation. Those observed effects believed caused by global warming with a medium level of confidence (> 50%) include agricultural and forestry changes due to growing season, pests, and fire; and human health impacts from extreme heat and infectious disease vectors.

Suspected effects with lower confidence levels from observation studies include increased flooding in mountainous regions, increased desertification, sea-level rise and effects on coastal wetlands and flooding, and extreme weather events. But there is a higher level of confidence that these effects will occur in the future.

Regarding human influence on these effects, the AR4 report concluded that "most of the observed increase in the globally averaged temperature since the mid-twentieth century is very likely (> 90%) due to the observed increase in greenhouse gas emissions."

Future impacts are significant and more certain. Advanced scientific study and observed evidence of global warming and its effects have helped scientists gain confidence about estimates of future impacts. Table 2.3 from the AR4 WG II report highlights the phenomena associated with global warming, their likelihood, and their impacts on agriculture, forestry, ecosystems, water resources, human health, and society. Some of the effects may be positive (e.g., increased agricultural yields in colder climates), but nearly all pose significant problems for adaptation.

Most of the impacts, such as disruption of agriculture and water resources, human health effects, and dislocation of populations in areas vulnerable to coastal storms and sea-level rise, are likely to affect poorer countries and populations much more than wealthy countries that also have the resources to adapt. Two of the major drivers of impact that are very likely to occur are extreme weather events and sea-level rise.

The Earth's poles will see the most dramatic temperature increases and effects, including receding Arctic sea ice, a reduction in permafrost areas on Arctic lands, and sea-level rise. Figure 2.14 from the Arctic Climate Impact Assessment (2004) shows that the Arctic ice cap already had receded 15% by 2002, and projected melting is more dramatic. Melting of polar ice, especially from land masses such as Greenland and Antarctica, would cause significant sea-level rise throughout the world.

Even if we act soon to reduce CO_2 emissions, future effects are likely to be far-reaching due to CO_2's slow removal times once it accumulates in the atmosphere. Figure 2.15 shows that even if efforts are made to eliminate CO_2 emissions within a century, the damage would already be done: future delayed effects on temperature and sea-level rise and other impacts would likely continue.

2.3.1.2 Responding to Climate Change

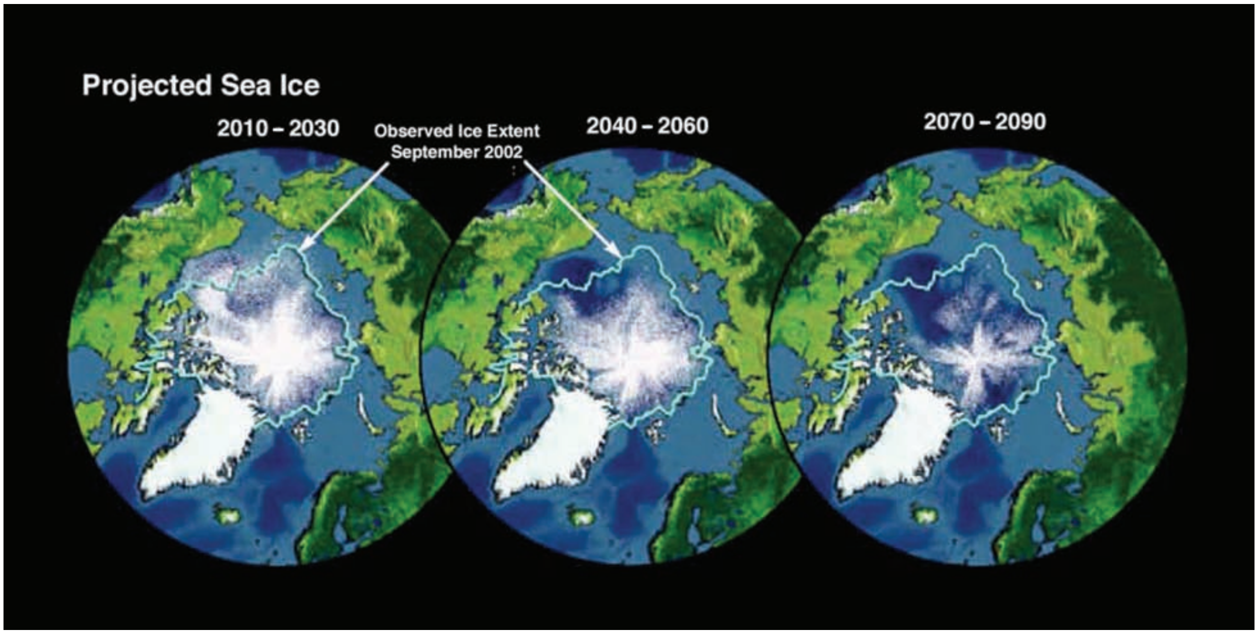
Despite the skeptics (see Sidebar 2.1), the increasing certainty about global warming is leading to a growing response by climate scientists; governmental bodies and nongovernmental organizations at global, national, state, and local levels; technology researchers; planners and policy makers; and people on the scale of a social movement. For example, in August 2006, a

table 2.3 Major Projected Impacts of Climate Change

		Examples of Major Projected Impacts by Sector			
Phenomena and Direction of Trend	Likelihood	Agriculture, Forestry, Ecosystems	Water Resources	Human Health	Industry/ Settlement/Society
Warmer and fewer cold days and nights; warmer or more frequent hot days and nights over most land areas	Virtually certain (> 99% probability)	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snow melt; increased evapotranspiration rates	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves: frequency increases over most land areas	Very likely (> 90%)	Reduced yields in warmer regions due to heat stress; wild fire danger increase	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young, and socially isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on elderly, very young, and poor
Heavy precipitation events: frequency increases over most areas	Very likely (> 90%)	Damage to crops; soil erosion, inability to cultivate land due to water logging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths; injuries; infectious, respiratory and skin diseases; post-traumatic stress disorders	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures
Area affected by drought: increases	Likely (> 66%)	Land degradation, lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases	Likely (> 66%)	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages cause disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations
Increased incidence of extreme high sea level (excludes tsunamis)	Likely (> 66%)	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection vs. costs of land-use relocation; potential for movement of populations and infrastructure; see tropical cyclones above

Source: IPCC, 2007

figure 2.14 **Expected Retreat of Polar Sea Ice in This Century**



Arctic ice cap had already receded 15% by 2002 and is expected to continue its retreat.

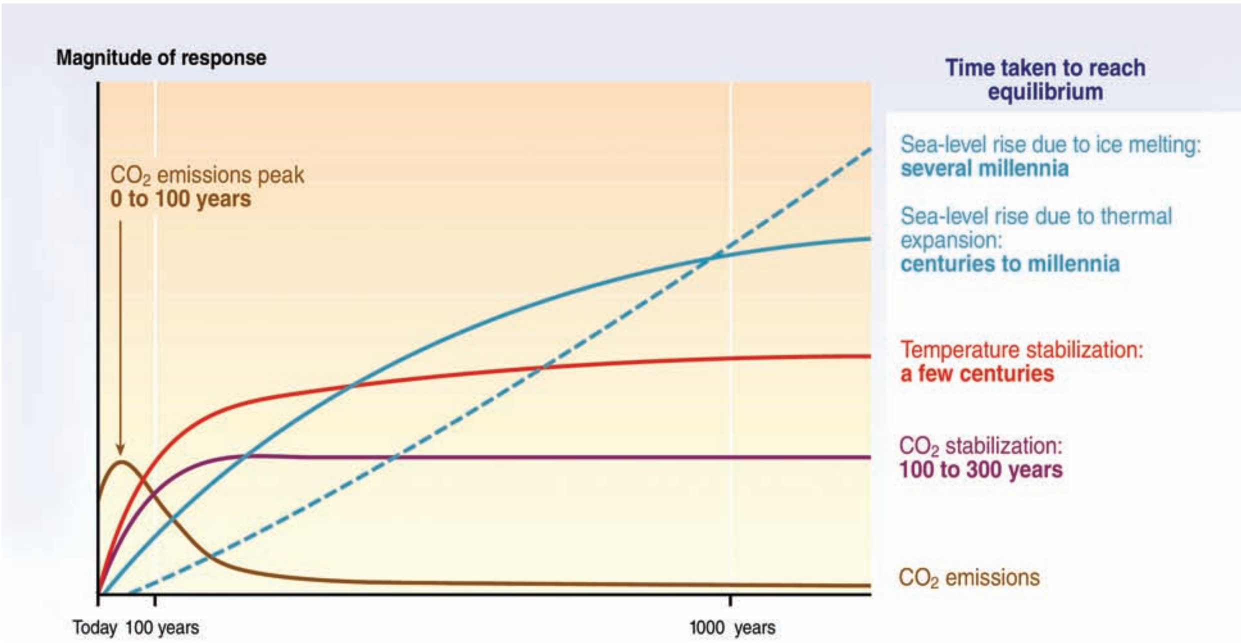
SOURCE: Arctic Climate Impact Assessment, 2004

group of sixty-four prominent California economists, including three Nobel laureates, wrote a letter to the California governor and legislature imploring action on climate change, stating "The Most Expensive Thing We Can Do Is Nothing!"

The emerging diverse response to the increasing effects of climate change can be characterized in two basic approaches:

1. *Mitigating* climate change by reducing GHG emissions through technology, planning, and policy. Examples include developing non-carbon energy sources and establishing targets and mandates for GHG emissions.
2. *Adapting* to climate change by
   a. lessening the impacts using technology and planning, such as building seawalls to counter sea-level rise, expanding irrigation to counter drought conditions, and building more dams and reservoirs to store runoff to make up for reduced snowpack water supply storage; and
   b. anticipating effects and modifying practices and patterns of development and agriculture now so that we can live with those effects in the future, such as relocating populations subject to severe effects of sea-level rise or extreme weather events and formulating new development designs that respond to new regional climatic conditions.

figure 2.15 **Time to Equilibrium: CO_2 and Its Impacts**



Carbon dioxide is retained in the atmosphere. Even if CO_2 emissions peak then decline, effects on CO_2 concentration, temperature, and sea-level rise may continue.

Source: IPCC, 2002

Mitigating climate change. There are two complementary approaches to mitigating climate change, or reducing CO_2 and other GHG emissions to decrease future effects of global warming. The first approach is through technologies to reduce emissions by using less energy, by replacing high-carbon with low- or zero-carbon energy, or by sequestering carbon. We discuss non-carbon energy sources later in this chapter, and focus on renewable energy and efficiency technologies throughout this book.

The second approach includes a range of energy and carbon policies that aim to accelerate the use of low- or zero-carbon energy technologies by regulation or financial incentives. These policies can be established at the international, national, state, or local level. Several existing and emerging policies of combating climate change are discussed in Chapters 17 and 18. Perhaps the most well-known policy initiative for reducing GHG emissions is the 1997 Kyoto Protocol, the most complex and controversial international agreement yet developed. The Protocol is discussed in Chapter 17, but we introduce it here because of its connection to IPCC.

IPCC's FAR in 1990 prompted the formation of the United Nations Framework Convention on Climate Change (UNFCCC), which was adopted in 1992 and signed by

SIDEBAR

SIDEBAR 2.1

The Global Warming Skeptics

Although the scientific community has a strong consensus about the evidence of current and future climate change, there are some who disagree. These skeptics are active on the Internet, on talk radio, on the lecture circuit, and in the popular press. They contend one or more of the following:

- That global warming is not occurring
- That if it is occurring, it is the result of normal climatic fluctuations rather than man-induced forcing
- That if it is occurring and possibly caused by man-induced forcing, it is not a serious problem; it is something we can adapt to
- That prospective impacts of GHG mitigation such as restrictions on fossil fuel use would have a far more damaging impact on our economy and society than the impacts of higher temperatures

The handful of scientific skeptics is connected through a number of institutes funded largely by energy industries with a large financial stake in the policy decisions about global warming. Led by S. Fred Singer, Frederick Seitz, Patrick Michaels, Richard Lindzen, and others, with affiliations with the George Marshall Institute, Cato Institute, Tech Central Station Science Foundation, and American Enterprise Institute, this group continues to raise uncertainties about the motives, methods, and results of the scientific process. But increasingly, these skeptics have been shown to receive significant funding from energy companies, including, for example, ExxonMobil as part of the company's 1998 strategy to delay government action on global warming. Seitz and Singer were shown to be wrong in their critiques of climate scientists in recent letters to the *Wall Street Journal* and *Science*. This is not to say that there is no uncertainty or that we need not continue to question our understanding of this complex system and how we monitor it. Countering the skeptics is a group of climate scientists who initiated an Internet blog in the search for truth. See www.RealClimate.org.

154 states and the European Union at the Rio Earth Summit that year; now, 189 countries are party to the Convention. The Convention addresses six GHG including carbon dioxide (82% of total GHG), methane (10%), nitrous oxide (6%), perflourinated hydrocarbons, hydrofluorocarbons, and sulfur hexafluoride.

The 189 countries of the Convention are classified according to their levels of development and their commitments for GHG emission reductions and reporting. They include the following:

- Annex I Parties: Forty developed countries plus EU's fifteen states that aim to reduce emissions to 1990 levels
- Annex II Parties: An Annex I subset of the most developed countries who also commit to help support efforts of developing countries

- Countries with economies in transition (EITs): An Annex I subset that does not have Annex II obligations, mostly made up of eastern and central Europe, and the former Soviet Union
- Non–Annex I Parties: All other, mostly developing countries, which have fewer obligations and should rely on external support to manage emissions

Each year the UNFCCC holds a Conference of Parties (COP). The third COP held in Japan in 1997 produced the Kyoto Protocol, which stated that by the first commitment period (2008–2012), developed countries would have to reduce combined emissions of GHG to at least 5% below 1990 levels. The Protocol would come into force when it was ratified by at least 55 countries, provided they constitute 55% of the CO_2 emissions of Annex I countries. This threshold was reached in November 2004, when Russia ratified the protocol, so it became legally binding to the 128 ratifying parties 90 days hence, on February 16, 2005.

The Protocol sets emissions reduction targets from 1990 for Annex II countries by the first commitment period (2008–2012). These targets range from –8% for many European countries and –7% for the U.S. to +8% for Australia and +10% for Iceland. Those countries with a positive target were allowed an increase in emissions.

Although Europe and other countries have aggressively implemented the Kyoto Protocol, the United States under the administration of George W. Bush decided not to ratify the protocol, arguing that it would seriously impact the U.S. economy and the Protocol would be ineffective without controls on emissions by developing countries. Because the United States is responsible for 21% of the world's carbon emissions, U.S. nonparticipation threatened the viability of the Protocol and the world's ability to meaningfully reduce global carbon emissions. But by 2007, scientific evidence and political pressure were mounting, and U.S. state and local action set the stage for a federal attention to carbon emission reduction. Chapters 17 and 18 discuss the Kyoto Protocol in greater detail, as well as related policies and programs by the European Union, other countries, and U.S. states and localities.

In May 2007, an IPCC international panel agreed in Bangkok to set future limits on emissions beyond Kyoto to try to achieve atmospheric CO_2 concentrations of 445 parts per million (ppm) because of evidence that levels above 450 ppm could trigger severe impacts such as melting of Greenland's ice mass. The target range of 445 to 650 ppm may become the basis for future international agreements for reducing GHG emissions.

Adapting to the effects of climate change. In addition to mitigating global warming through emission reduction, the probable effects in spite of those efforts require us to figure out how to live with climate change. Adaptation measures include lessening the impacts through engineering means without major changes in patterns or locations of development. But attempts to mitigate future impacts in coastal areas, for example, caused by more extreme weather events and sea-level rise, may exceed technological or financial capabilities.

So adaptation must also include anticipating the impacts of climate change and planning for them. This may include emergency preparedness, future land use planning and controls, relocation of existing developments and communities, and alternative water supplies. These measures will be costly and plagued with uncertainty, and will be especially difficult for developing countries that have limited budgets and expertise. Unfortunately, it is these same countries that are likely to experience the most severe impacts.

2.3.2 Local and Regional Air Pollution

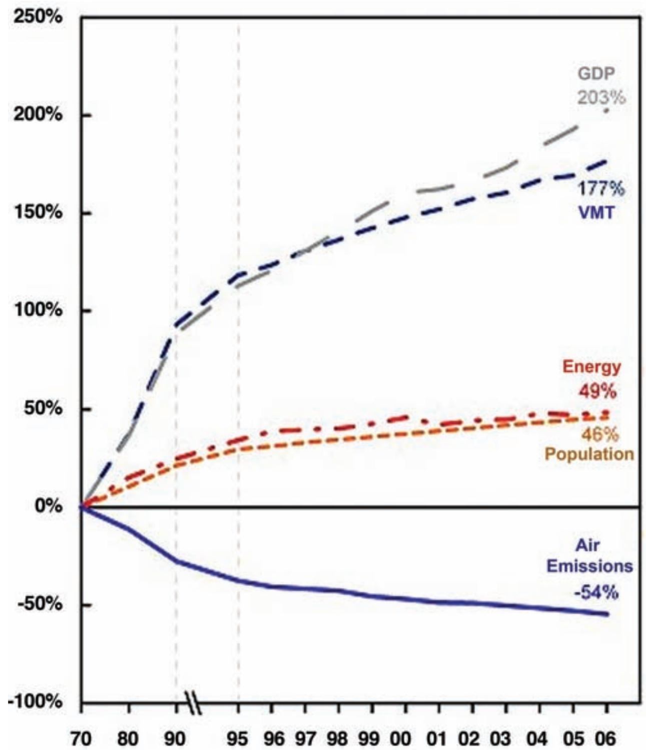
Fossil fuel combustion is the major source not only of carbon dioxide emissions, but also of air pollutants affecting human health and ecosystems. All major air pollutants, including fine particulate matter (PM), oxides of sulfur (SO_x) and nitrogen (NO_x), carbon monoxide (CO), ozone (O_3), and some heavy metals such as mercury, are linked to fossil fuel combustion. As shown in Table 2.4, 90% of the major air pollutants in the United States in 2006 were from fuel combustion. Not only do these pollutants affect human health in cities throughout the world, but some are also subject to long-range transport, creating acid rain and other deposition that degrades waters and ecological systems.

The good news is that we have made considerable progress in reducing emissions of air pollutants in the United States, largely through technological controls. Figure 2.16 and Table 2.4 show that aggregate emissions of the criteria air pollutants have been cut in half between 1970 and 2006. Perhaps, surprisingly, most of those gains have been made since 1990: 39% drop in CO emissions between 1990 and 2003, 35% drop in volatile organic compounds (VOC), 40% drop in SO_x, 28% drop in NO_x, and 30% drop in smaller (more hazardous 2.5 micrometer diameter) particulates. This reduction has occurred while energy use, population, vehicle miles traveled, and the economy have all increased (Figure 2.16).

As shown in Table 2.4, stationary energy users such as power plants and industry are major sources of SO_x, PM, and NO_x, as well as several toxic pollutants such as mercury. Power plants, mostly older coal-fired plants, emit 67% of total SO_x, 22% of NO_x, 41% of mercury, and 39% of CO_2. Mobile sources such as automobiles are major contributors of CO, VOC, and NO_x, the latter two of which are the precursors of urban smog and ozone. Technology controls required by government regulations have been incorporated in industrial and power plants and motor vehicles, and progress has been made in reducing air pollutant emissions and resulting episodes of excessive air pollution, especially in industrialized countries.

The bad news is that even with these emissions reductions, nearly half the people in the United States still live in areas not fully attaining clean air standards. Figure 2.17(a) shows the improving overall trend of ozone concentrations in U.S. cities relative to the eight-hour standard. Figure 2.17(b) shows the 124 ozone non-attainment areas. Air quality is far worse in the cities of poor countries, where people continue to experience serious public health hazards from energy-related air pollution. Figure 2.18 gives average annual air pollution levels in twenty Asian cities along with World Health Organization (WHO) standards. WHO estimates that more than 500,000 premature deaths per year in Asia are caused by air pollution.

figure 2.16 **U.S. Air Pollutant Emissions Trends, 1970–2006**



Overall emissions have been reduced by 54% while GDP has more than tripled, vehicle miles traveled have soared, and energy and population have both increased by nearly 50%.

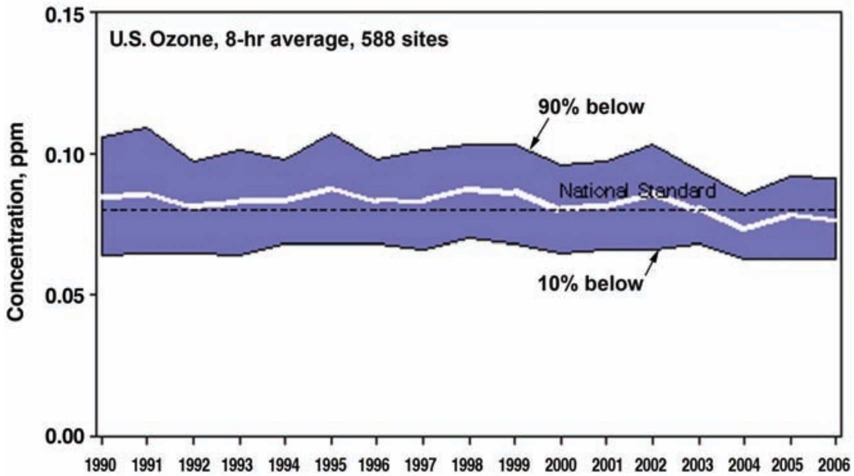
Source: U.S. EPA, 2007

table 2.4 **Aggregate U.S. Air Pollutant Emissions (1970, 1990, 2006) and Sources**

	1970	1990	2006	% energy	% stationary	% mobile
Sulfur dioxide (SO_x)	31	23	14	87%	83%	4%
Carbon monoxide (CO)	197	144	88	94%	5%	89%
Particulate matter PM 10	12.2	3.2	2.6	60%	39%	21%
Particulate matter PM 2.5	NA	2.3	1.6	63%	40%	23%
Nitrogen oxides (NO_x)	27	25	18	95%	39%	56%
Volatile organic compounds (VOC)	34	23	14	53%	7%	46%
Lead	0.22	0.005	0.002	NA	NA	NA
Total	**302**	**218**	**137**	**90%**	**20%**	**70%**

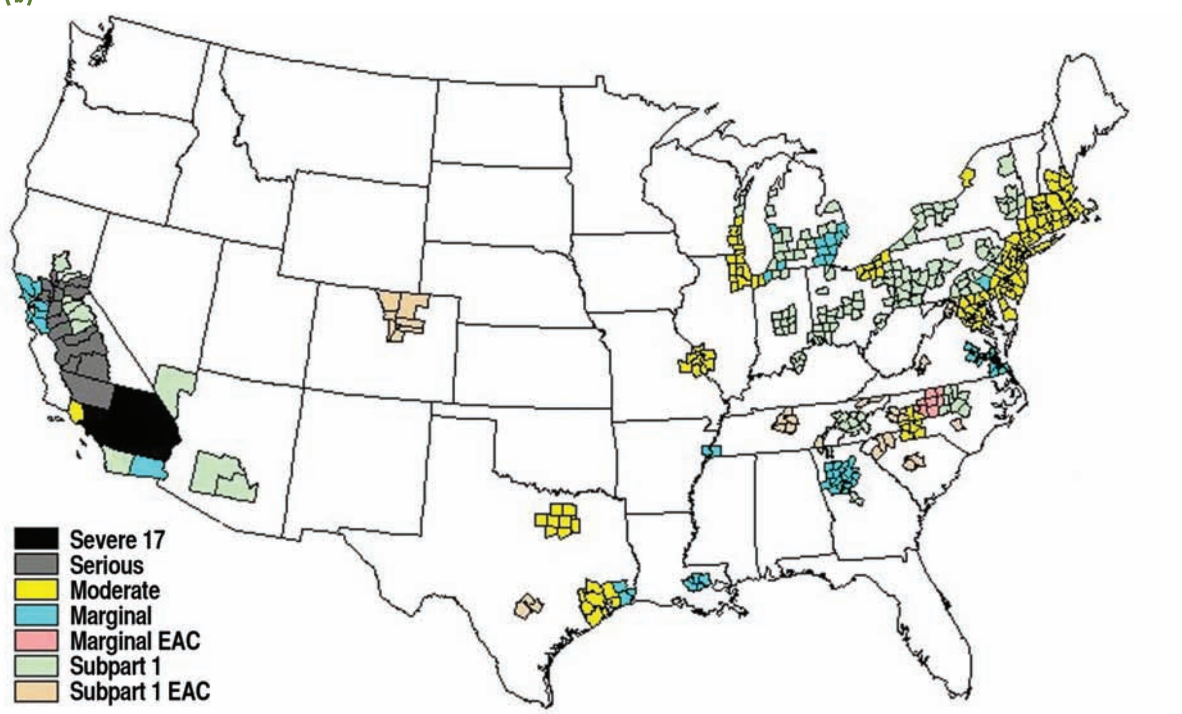
Source: U.S. EPA, 2007

figure 2.17(a) Some Progress in U.S. Urban Ozone Concentrations



Source: U.S. EPA, 2006

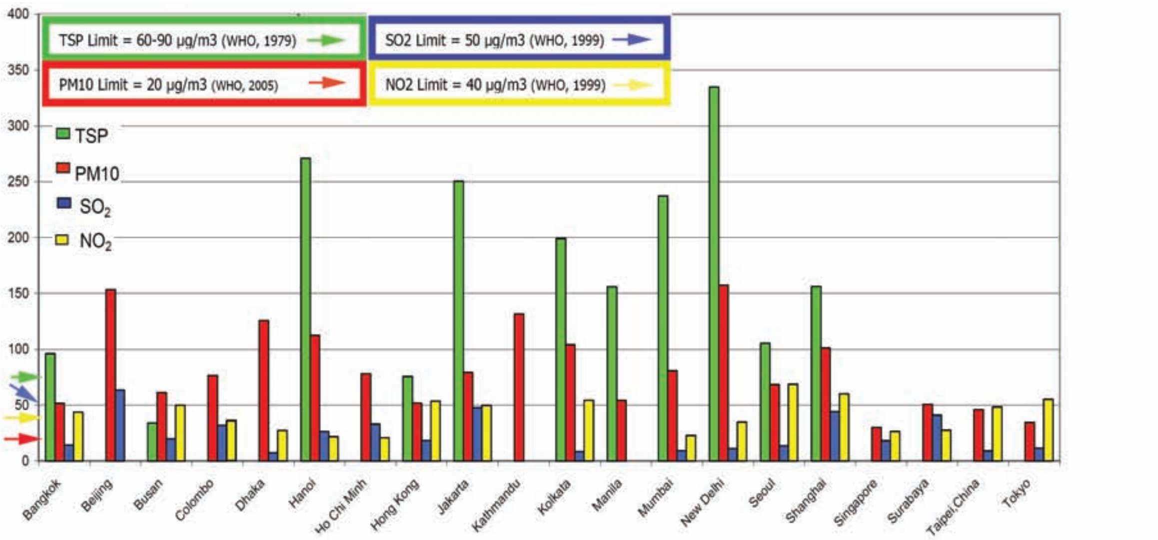
figure 2.17(b) U.S. Non-attainment Areas for Ozone



Many U.S. cities are still not attaining health standards for ozone.

Source: U.S. FHWA, 2006

figure 2.18 **Air Pollution Concentrations in Selected Asian Cities, 2000–2004**



Relative to WHO standards, most cities far exceed particulate matter standards.

Source: CAI-Asia, 2006

According to the *Financial Times,* a 2007 World Bank draft report estimated 750,000 premature air pollution–related deaths in China alone, but this figure was removed from the final report because the Chinese government believed it would cause social unrest.

Improvement of emissions and air quality in the United States has been largely the result of the Clean Air Act, originally passed in 1970 and reauthorized in 1977 and 1990. Congress continues to debate changes in the law, focusing on the pace of additional emission reductions at coal-burning power plants (see Chapter 17).

2.3.3 Other Effects of Fossil Fuels

Our energy use has impacts beyond climate change and air pollution. Table 2.5 highlights many of these environmental impacts by energy source, including fossil fuel, nuclear, and renewable energy. The extraction and transport of energy also impacts the environment and should be considered public costs of our energy system. For example, coal mining has long impacted coal regions: deep mining hazards, strip mining, mountaintop removal and valley fill methods, acid mine drainage, and mineland reclamation have prompted public and political response. Oil transport requires risk of tanker spill. Transport risks for liquefied natural gas (LNG) are different because of the volatile nature of LNG. Some worry about terrorism risks of LNG tankers and facilities and nuclear power plants.

table 2.5 Environmental Impacts of Energy Sources Other Than GHG Emissions

Energy Source	Environmental Impacts	Significance	Mitigation
Coal—electric	Mining and processing impacts on lands/waters	• Severe	• Mineland reclamation
	Combustion: carbon emissions	• Severe	• Carbon sequestration
	Air pollution (part, SO_x, NO_x, mercury); acid/particulate deposition	• Severe	• Technology controls
	Thermal pollution	• Moderate	• Cooling controls
	Ash disposal	• Moderate	• Storage/land application
Coal—synthetic fuels	Mining impacts on lands/waters	• Severe	• Mineland reclamation
	Processing impacts on waters	• Severe	• Technology controls
	Residue disposal on lands	• Severe	• Storage/land application
	Combustion: carbon emissions	• Severe	• Carbon sequestration
	Air pollution (part, SO_x, NO_x)	• Severe	• Technology controls
Petroleum—transportation fuel	Tanker/pipeline spills	• Risk	• Management controls
	Refinery impacts	• Moderate	• Technology controls
	Combustion: carbon emissions	• Severe	• Carbon sequestration
	Air pollution (NO_x, HC, CO)	• Severe	• Technology controls
Oil shale, oil sands	Mining impacts on lands/waters	• Severe	• Mineland reclamation
	Processing impacts on waters	• Severe	• Technology controls
	Residue disposal on lands	• Severe	• Storage/land application
	Combustion: carbon emissions; air pollution (part, SO_x, NO_x)	• Severe	• Technology controls
Natural gas	Pipeline leakage	• Moderate	• Management controls
	Liquefied natural gas transport risks	• Risk	• Management controls
	Combustion: carbon emissions, NO_x	• Moderate	• Technology controls
Nuclear power	Radioactive materials, fuel cycle	• Risk	• Management controls
	Plant safety	• Risk	• Management controls
	Waste storage and disposal,	• Risk	• Technology controls
	Nuclear materials proliferation	• Risk	• Management controls
Hydro—large	Hydro system, fish migration, riparian ecology	• Severe	• Fish passage
	Reservoir flooding impacts	• Severe	• Relocation/compensation
Hydro—small	Hydro system	• Minor	
Solar thermal—on site	Manufacturing impacts	• Minor	
Solar PV—on site	Manufacturing impacts	• Moderate	• Technology controls
Solar PV—farms	Manufacturing impacts	• Moderate	• Technology controls
	Land consumption	• Moderate	• Mixed use
Wind electric—small	Manufacturing impacts	• Minor	
Wind electric—farms	Manufacturing impacts	• Moderate	• Technology controls
	Land consumption, bird mortality, aesthetics	• Moderate	• Mixed use
Biofuels—liquid	Farmland consumption	• Moderate	
	Farming/harvesting impacts on waters	• Moderate	• Technology controls
	Processing impacts	• Moderate	• Technology controls
	Combustion: carbon, NO_x	• Moderate	• Technology controls
Biomass—solid	Forestland consumption	• Moderate	
	Farming/harvesting impacts on waters	• Moderate	• Technology controls
	Processing impacts	• Minor	• Technology controls
	Combustion: carbon, particulates, NO_x	• Moderate	• Technology controls

2.4 Opportunities and Limits for Non-fossil Energy

As discussed above, mitigating climate change by reducing carbon emissions requires technological advances in non-carbon sources and carbon sequestration. There are six principal means to reduce carbon emissions:

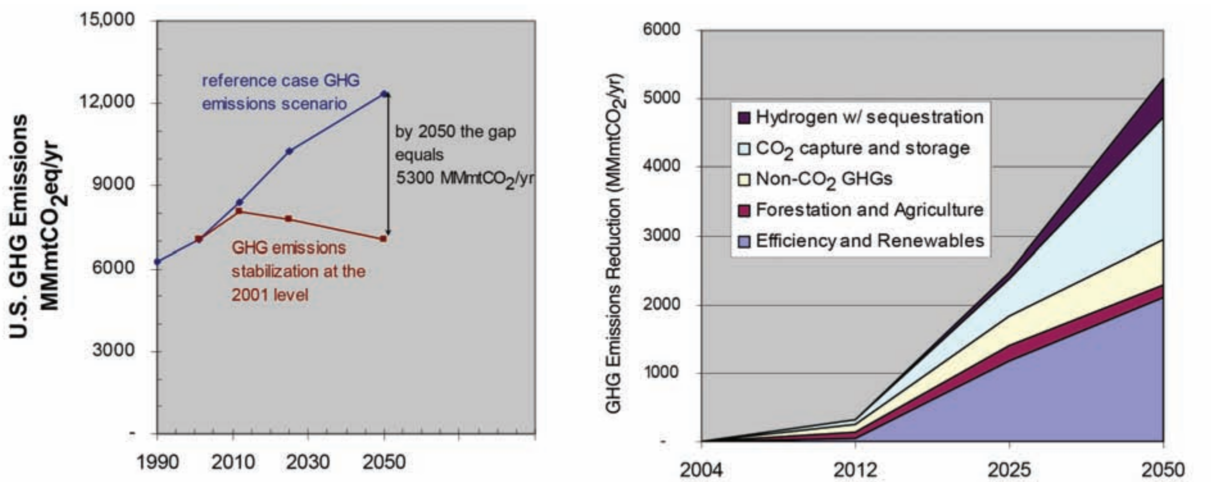
1. Reduce fuel combustion and carbon emissions by improving the energy efficiency of buildings, vehicles, appliances, and power generators.
2. Use renewable energy, with wind/solar/geothermal replacing coal electricity and with biofuels replacing petroleum.
3. Shift from high- to low-carbon fuel, in which, for example, natural gas electricity replaces coal electricity.
4. Capture and store CO_2 in deep oceans and deep mine cavities. Carbon sequestration is a principal part of the U.S. policy to reduce CO_2 emissions without major disruptions of the current fossil fuel energy-industrial complex, and possibly to move to a coal-based hydrogen economy.
5. Use nuclear power to replace coal electricity.
6. Sequester carbon via reforestation and agricultural soil conservation. Natural forests and soils are major sinks for global carbon and just as deforestation and conventional agricultural cultivation release carbon to the atmosphere, reforestation and soil conservation practices capture carbon.

Figure 2.19 shows U.S. DOE's projected U.S. GHG emissions and relative means for stabilizing emissions at 2001 levels by 2050. Efficiency and renewables provide the greatest reduction. Chapter 3 discusses Princeton professors Scott Pacala and John Socolow's assessment of CO_2 reductions by these technical methods as well as IPCC future socio-political scenarios for carbon reduction. This section addresses some of the limits and opportunities of non-carbon energy: nuclear, renewables, and efficiency.

2.4.1 Nuclear Power

When commercial use of nuclear power was developed in the late 1950s, it was thought to be the great savior of human civilization. It would become our source of clean, limitless electricity "too cheap to meter" replacing dirty coal and ultimately depletable oil as we moved to the twenty-first century.

But, nuclear power has yet to come close to achieving that promise. Concerns about rising costs, safety, waste disposal, and proliferation of nuclear materials have reduced the favor of nuclear power in the eyes of the public, utilities, investors, and policy makers, and growth of nuclear power has been stagnant for nearly two decades. Some people, including some prominent environmentalists, have called for a renaissance of nuclear power in response figure 2.19 **U.S. DOE Scenario for GHG Emission Stabilization by 2050**



Stabilization requires reduction of 5300 MMmt CO_2 below reference-case. The best means of achieving reduction are efficiency, renewables, and carbon sequestration.

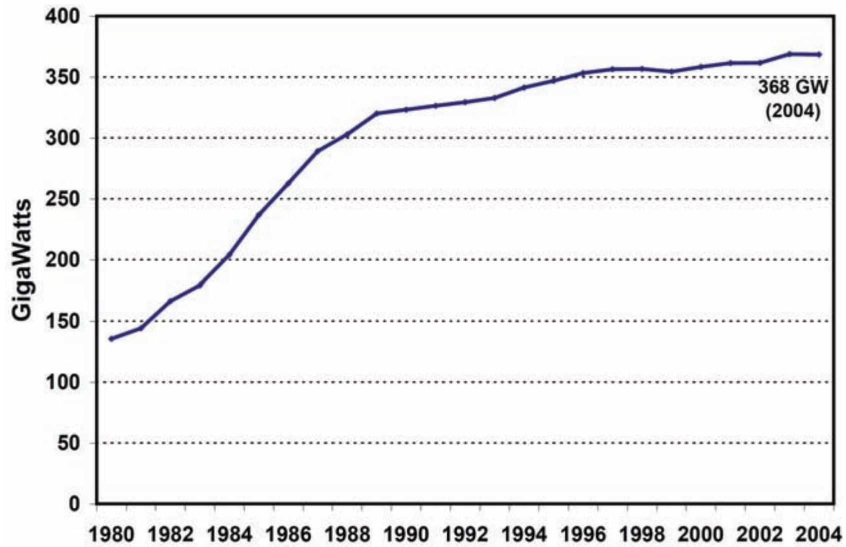
Source: U.S. DOE, 2004

to oil and carbon problems, but life-cycle issues of long-term waste management and nuclear weapons proliferation in an unstable world remain significant barriers.

2.4.1.1 From Great Hope to Stagnant Growth

From 1970 to 1990, nuclear power steadily increased its contribution to 19% of U.S. and 17% of global electricity. However, since 1990 the addition of installed nuclear capacity has been stagnant. Figure 2.20 shows the growth of world capacity from 1980 to 2004. Table 2.6 shows that since 1998, capacity growth has been only 0.5% per year when total world energy grew by 2% per year. Thirty countries have nuclear power, but the top ten countries provide 86% of the world nuclear energy. The top three (United States, France, and Japan) generate 57% of the world total. While generation has increased due to improved capacity factor of operation, the nuclear-to-total-electricity ratio of contribution has not changed.

The United States is still the world leader in nuclear power, but no new nuclear power plants have come on line since 1996, and U.S. nuclear capacity of 100 GW is the same as in 1990. Figure 2.21 gives the U.S. nuclear capacity and generation from 1980 to 2006. Although nuclear capacity has not changed since 1990, its increased capacity factor has helped increase generation. **Capacity factor** is the percent of time the plant operates at full capacity (see Chapter 9). Current plants were designed for a lifetime of thirty years and most operating licenses will expire in the next twenty years. The Nuclear Regulatory Commission issued twenty-year figure 2.20 **Global Growth of Nuclear Power, 1980–2004**



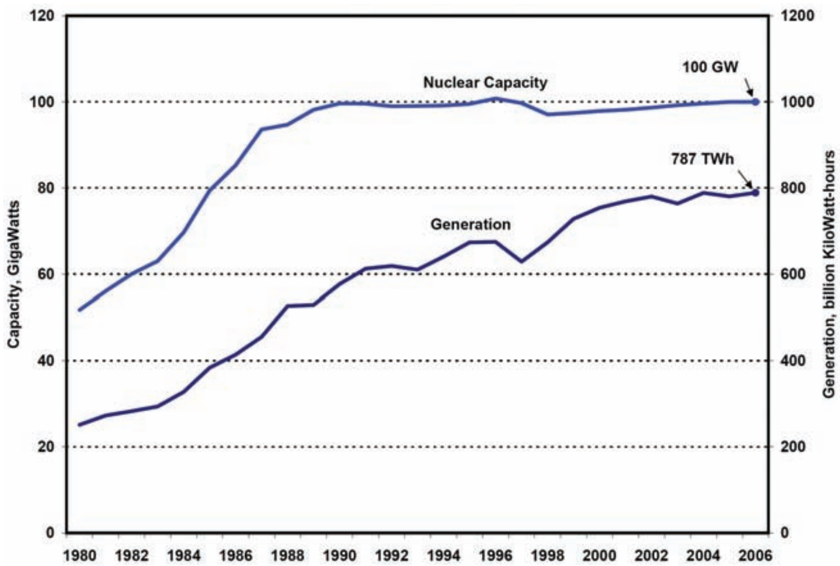
Growth has been flat since 1990, especially since 1998.

Source: data from U.S. EIA, 2006b

table 2.6 **World Nuclear Capacity and Generation**

Country	% World Capacity, 2004	% World Generation, 2004	Annual % Change Capacity, 1998–2004
United States	27.0%	30.1%	0%
France	17.2%	16.3%	+0.8%
Japan	12.4%	10.4%	+1.0%
Russia	6.0%	5.2%	0%
Germany	5.8%	6.1%	+0.1%
South Korea	4.3%	4.7%	+7.3%
United Kingdom	3.3%	2.8%	–0.9%
Ukraine	3.2%	3.2%	–2.3%
Canada	2.9%	3.3%	–6.2%
Sweden	2.6%	2.8%	–4.6%
World	**368 GW**	**2219 TWh**	**+0.5%**

license extensions for sixteen plants by 2006, and utilities are expected to apply for nearly all of the operating plants. Although utilities have had safety violations, they have maintained and operated these plants without major incident and hope to extend their lives. However, figure 2.21 **U.S. Nuclear Capacity and Generation, 1980–2006**



U.S. nuclear capacity has been flat since 1990, but improved capacity factor has helped increase generation.

SOURCE: data from U.S. EIA, 2007a

many fear that much like any older machine that is more prone to malfunctioning, an aging nuclear plant increases the likelihood of accidents if it is allowed to operate well beyond its design life.

The future of nuclear power depends on new development, not simply license extensions. With the advent of global warming, many prominent environmentalists, including James Lovelock, Bruce Babbitt, and others, are calling for a reevaluation of nuclear, believing it the only viable energy solution to global warming. Although very few plants have been built in recent years, research on new nuclear plant designs has continued. In the United States, there is a renewed interest in nuclear power; considerable funding, as well as streamlined licensing, was included in the 2005 Energy Policy Act.

2.4.1.2 Barriers to a Renaissance in Nuclear Power

Nuclear power has the benefit of no carbon emissions, but requires the handling and use of radioactive materials that must be kept isolated from humans and other living systems. Exposure to radioactive materials is linked to genetic mutation and human cancers. To prevent release of radioactive materials, the nuclear power industry requires near-perfect management of technologies and human systems involved in the entire nuclear materials cycle from mining, processing, and transport of fuel to power plant operation to waste storage, transport, and disposal.

The biggest obstacles facing a resurgence of the nuclear industry are continuing uncertainty over safety and waste management, uncertainties over costs, increasing concerns over proliferation of nuclear materials in a world plagued by terrorism, and public and investor reluctance. Needed safeguards for safety, waste management, proliferation control, plant decommissioning, and other unknown requirements translate not only into technical, public, and political questions, but also into higher development and operating costs. A major 2003 study by MIT addressed these obstacles and concluded that, while daunting, we need to overcome them so that nuclear can reemerge as a viable option (along with efficiency, renewables, and carbon sequestration) for our energy future to combat global warming (see Sidebar 9.2). Even if many of the challenges facing nuclear power can be overcome and the optimistic scenario of tripling nuclear capacity by 2050 can be realized, it would amount to no more than 20% of global electricity, and cut the expected 100% increase in emissions of carbon by only 12% to 27%. Nor could nuclear provide a direct or substantive answer to our dependence on oil.

2.4.2 Energy Efficiency

Our best bet for both short-term investment to reduce fossil fuel dependency and for long-term sustainability is to increase the efficiency of energy production and use and to develop sustainable renewable energy sources. But energy efficiency comes first because it provides the best short-term opportunity to reduce demand for oil and carbon emissions, is the most cost effective of our energy options, has lasting value as benefits continue to accrue, and resulting lower demand makes supply options easier.

Great progress has been made in the energy efficiency of buildings, appliances, and vehicles in the last three decades, and the global and U.S. economies are far more energy efficient as a result. Figure 1.8 highlighted the improvements in the United States and the estimated $700 billion in energy costs saved as a result of efficiency improvements since the mid-1970s. But artificially low energy prices have constrained investment in efficiency and there is great potential for further improvements. This section introduces some key definitions in efficiency and conservation, and subsequent chapters explore the wide-ranging opportunities for efficiency improvements in buildings, electricity, and transportation.

We have already introduced an important measure of the effectiveness of our energy, that is the **energy intensity** of our economy. Energy intensity of the U.S. and world economies has improved steadily since the mid-1970s (Figures 1.3 and 1.7; Table 1.2). Intensity is measured by energy per dollar GDP, and it has improved by 25% in the world since 1980 and 45% in the U.S. since 1973. Per capita energy increased only 2% during this period for the world and actually decreased by 5% for the United States, all during periods of improved standards of living and economic growth. Recall from Equation 1.1:

Eq. 2.1

$$\textbf{Energy intensity} = \frac{\textbf{Energy used}}{\textbf{\$GDP}}$$

Section 1.4.2 explained that the improvement in energy intensity in the United States during the past three decades resulted from the following:

- Investments in efficiency driven by higher energy prices and government standards mostly until 1985
- Structural changes in the economy driven by advances in the less energy-intensive service and information sectors, mostly since 1995

Energy efficiency is different from energy intensity. **Energy conversion efficiency** is the effectiveness of converting from one form of input energy to another more useful form, such as converting input coal chemical energy to thermal energy in a power plant boiler to mechanical energy in the turbine to useful electrical energy in the power plant generator. If we can convert more useful energy out of a unit of input energy we are converting energy more efficiently.

Eq. 2.2

$$\textbf{Energy conversion efficiency} = \frac{\textbf{Useful output energy}}{\textbf{Input energy required}}$$

Energy functional efficiency is the useful performance we can get out of the energy we consume. We do not really want energy; we want the functions that it provides. We want thermal comfort; lighting; transportation of people and materials; entertainment; food production, preservation, and preparation; industrial processes; mechanical tools; and other life and labor improvements that energy provides us. If we can provide these functions with less energy, we are using energy more efficiently.

Eq. 2.3

$$\textbf{Energy functional efficiency} = \frac{\textbf{Functions provided}}{\textbf{Useful energy consumed}}$$

By its nature, energy conversion and functional efficiency improvements do not require any change in the end result, that is, the functions provided, people's behavior, and standard of living.

Energy conservation is defined here as behavioral changes made by individuals or communities to save energy by cutting back on the functions energy provides. So, for example, in your house:

- Improvement in energy *conversion efficiency* can be realized by replacing an old gas furnace with a new super-efficient one (same useful output, less input).
- Improvement in energy *functional efficiency* can be realized by adding insulation to the house (same function, less useful energy consumed).
- Energy *conservation* can be realized by lowering the thermostat at night during the heating season (less function, less energy).

Since 1975, local and state building codes have improved energy efficiency in new buildings, federal Corporate Average Fuel Efficiency (CAFE) standards have improved auto efficiency, and federal standards have improved electrical appliance efficiency. For example, state and federal efficiency standards for refrigerator efficiency have driven down the energy use per new unit by 75% since 1974, or 5% per year (see Chapter 8).

CAFE standards require automakers to meet an average efficiency in miles per gallon (mpg) for the fleet of cars and light trucks they sell. The standards increased steadily until 1985, but car standards have not increased since. In 2003, light truck standards were increased from 20.2 mpg to 21.0 for model year (MY) 2005, 21.6 for MY2006, and 22.2 mpg for MY2007. But, because of market shift to more light trucks (i.e., SUVs, vans, and pickups), overall new vehicle efficiency has actually decreased since 1985 (see Chapter 13).

The good news is that energy intensity has steadily improved in the United States and throughout the world since the mid-1970s; the bad news is that investments in energy efficiency have slowed in the United States. Reasons for this are as follows:

- Relatively cheap energy prices, especially when compared to rising incomes
- Transaction costs and investment barriers such as uncertainty over future energy costs, new products, and knowledge gaps

However, there is a huge potential for cost-effective energy efficiency improvements in buildings, vehicles, appliances, lighting, and industrial processes. These opportunities are addressed in subsequent chapters.

2.4.3 Renewable Energy

Renewable energy systems avoid many of the problems of conventional energy, including resource depletion, carbon emissions, air pollution, radioactive materials, fuel transport from source to use, and so on. Renewable energy sources are diverse and well suited for a variety of energy applications. They include direct solar thermal energy; solar electricity through photovoltaics; wind electrical generation; hydroelectric generation; biomass energy in gaseous, liquid, and solid forms; geothermal heating and electricity; and tidal and wave energy.

However, renewable energy still contributes very little energy to both the U.S. and world economies. Renewables contribute only about 6%–7% of commercial energy of both the United States and the world. This does not include non-marketed renewable energy, such as wood and other biofuels (estimated to be about 10% of total world energy use) and on-site solar heating and photovoltaic systems. Hydro and wood contribute over 80% of U.S. commercial renewable energy. The primary use of wood is the wood products industry use of residual materials for internal heat and power generation.

Newer sources, such as solar photovoltaics, wind electricity, and liquid and gaseous biofuels, have been plagued for decades by higher capital costs in the face of cheap fossil fuels.

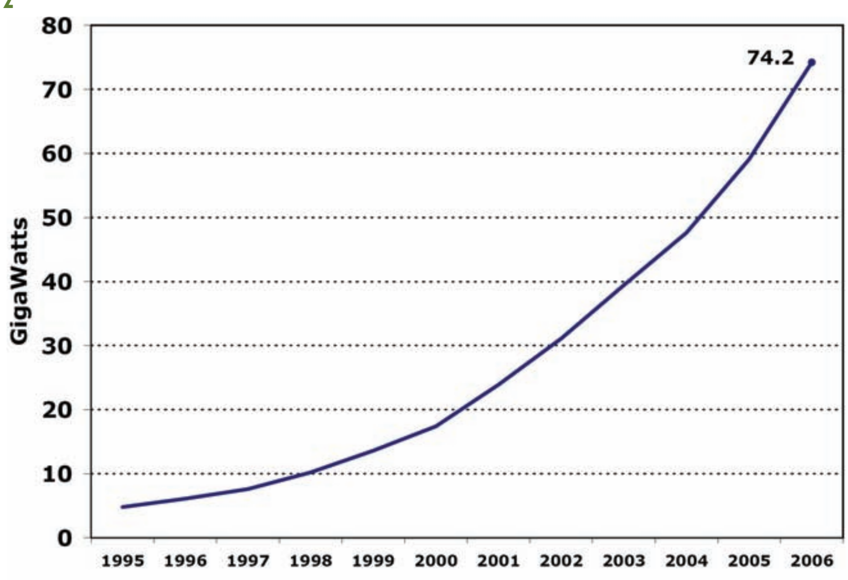
But today these three sources have the fastest growth rate of any energy source, growing at 20% to 40% per year.

Worldwide wind electric generating capacity grew to more than 74 gigaWatts (GW) by the end of 2006, about ten times the capacity in 1997 (Figure 2.22). The annual growth rate of 30% per year during that period makes wind the energy source with the fastest growth rate. Germany leads with 20.6 GW, followed by Spain and the United States both with 11.6 GW.

Photovoltaic (PV) electric system installed capacity grew by 1500 MW in 2005, a 34% annual growth rate (Figure 2.23). World capacity exceeds 6.5 GW at the end of 2006.

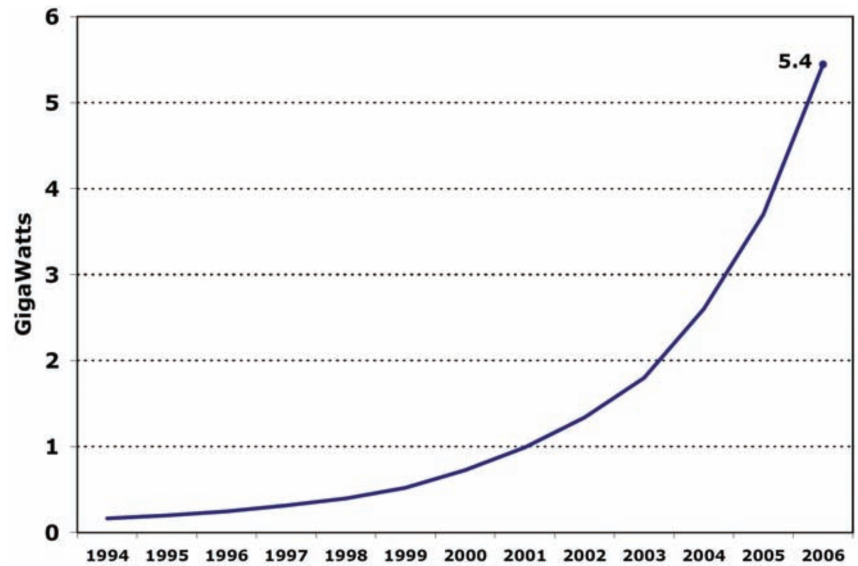
Biofuels for transportation liquid fuels have also seen considerable growth. Ethanol production more than tripled in six years to 13.5 billion gallons in 2006 (Figure 2.24). Representing only about 11% of fuel ethanol production, biodiesel production is growing even faster. The United States surpassed Brazil as the world's largest ethanol producer in 2005. Growth continues but U.S. production from corn must be replaced by cellulose-based ethanol if this growth rate is to continue.

figure 2.22 **Growth of World Wind Power Capacity, 1995–2006**



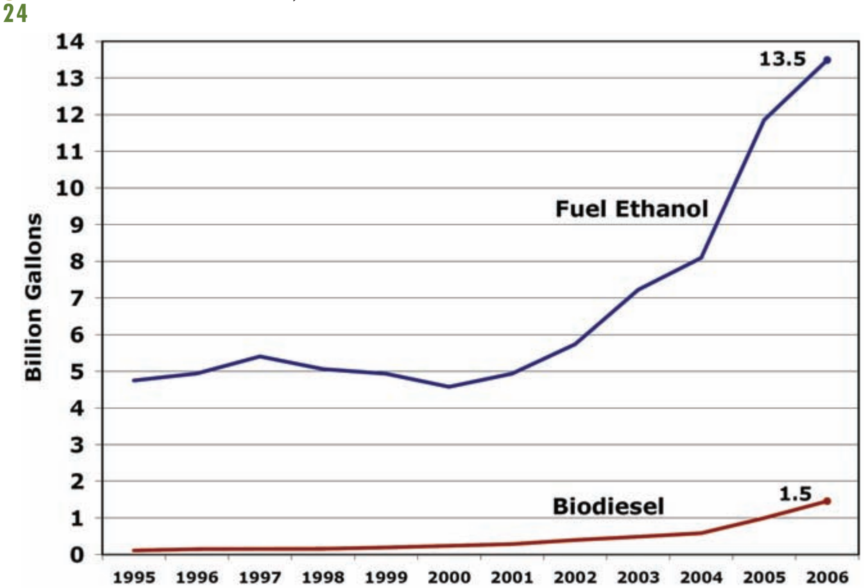
Source: data from AWEA, 2007

figure 2.23 Growth of World Photovoltaic Power Capacity, 1994–2006



SOURCE: data from SolarBuzz™, 2007

figure 2.24 Growth of World Biofuels, 1995–2006



SOURCE: data from RFA, 2007, and NBB, 2007

SOLUTION

SOLUTION BOX 2.1

World wind, solar photovoltaic, and biofuel energy currently provide only about 1% of the 463 quads of global marketed energy. But they are growing fast. If worldwide growth of wind, solar photovoltaic, and biofuel energy continues at an annual rate of 30% and global energy use grows at 2% per year, what percentage would these fuels provide in fifteen years in 2020?

Solution: Estimated 2005 wind, solar, biofuels energy is 1% of 463 or 4.63 quads.

Estimated 2020 wind, solar, biofuels energy $= F_{wsb} = P(1 + r)^n$

$$= F_{wsb} = 4.63(1.3)^{15} = 237 \text{ quads}$$

$$\textbf{Estimated 2020 total global energy} = F_{ge} = 463(1.02)^{15} = 623 \text{ quads}$$

$$\textbf{Wind, solar, biofuels percentage in 2020 with current growth} = \frac{237}{6323} = 38\%$$

Can we continue the current rate of growth of wind, solar, and biofuels? Probably not. But these sources are growing fast and will increasingly affect our future energy mix.

2.5 Summary

The implications of our current patterns of energy use present a troubling picture. The world and the United States remain highly dependent on fossil fuels (86%) and oil (40%). Despite warning signs of the consequences of this dependence on the world economy and environment during the past thirty years, little has been done to alter these patterns of use except for improvement in the energy intensity of our economy. The following points are important to keep in mind as we delve more deeply into our energy system:

- Oil is a nonrenewable resource and production continues to increase to meet growing demand, especially in the less developed countries as their economies develop. While some pessimists surmise that we have already reached peak production or will in the next few years, even some optimists project a peak within twenty years. This has severe implications for the advance of the global economy.
- There is a scientific consensus that global climate change forced by human-induced greenhouse gas emissions is occurring. The vast majority of those emissions are carbon dioxide from the combustion of carbon-based fossil fuels, coal, oil, and natural gas. Scientists believe that the future impacts for climate change will be not only severe but also long-lasting with significant lag effects, so the impacts of emissions today will be felt long into the future.

- Among the United States reservations about the Kyoto Protocol is that they believe there are few viable short-term options to reduce CO_2 emissions by switching to non-carbon energy sources. To some extent they are correct:
  - Nuclear power is stagnant in the United States (and worldwide for that matter). Prospects are improving, but growth will likely be slow before 2030 because of concerns over costs, safety, waste management, and nuclear weapons proliferation.
  - Renewable energy contributes only a small share of U.S. and global commercial energy and its main sources, hydro and wood residue in the forest product industry, have limited growth potential. Still, wind, solar PV, and biofuels are growing quickly.
  - Energy efficiency improvements have helped reduce energy intensity of the economy but significant opportunites for cost-effective improvements have not been achieved.

Add to these points the lessons from Chapter 1:

- Global consumption of energy continues to increase at 2% per year, with prospects for much additional growth as the world's emerging countries, led by China and India, develop modern economies.
- The geopolitical realities of oil have caused increased dependence on the politically unstable Middle East and access to oil has had a significant impact on trade balance and foreign and military policy.
- Fossil fuels with their CO_2 emissions and other environmental effects still provide more than 85% of our energy.

With this troubling array of issues as a backdrop, the following chapter explores a variety of future energy scenarios.