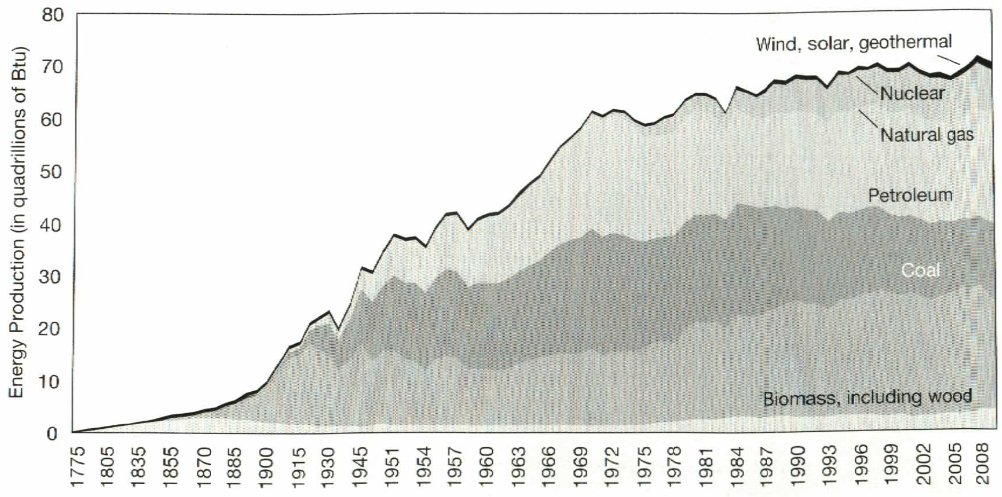
SOURCE: NATIONAL SNOW AND ICE DATA CENTER.

FIGURE 7.6 The extent of polar sea ice at its minimum in 2009. The dotted line shows the median extent of the sea-ice minimum for the last twenty years of the twentieth century. Note that Norway and Sweden would fit into the new area of open water.

ENERGY AND THE CONTROL OF NATURE

The most successful species learned to capture and control the energy of the Sun with the invention of agriculture ten thousand years ago. Sunlight is captured by crop plants and some of that energy is used by humans, either directly or indirectly, when plants are fed to animals consumed by people. More than two hundred years ago, we learned how to efficiently mine and utilize the energy in coal



SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION.

FIGURE 7.7 U.S. energy production, 1775–2009, by source. The different sources are added to one another, so that the bottom line shows biomass (wood, up until 1945), while the next line adds coal production, and so forth.

and launched the Industrial Revolution. Figure 7.7 shows the striking increase in energy consumption, beginning in the early nineteenth century, as humans learned to harness energy from sources beyond their own bodies and those of domesticated animals.

The industrial economy draws its energy mainly from fossil fuels, though nuclear energy and hydropower are quite important in some nations. Fossil fuels are mineral resources that were once living things: coal is formed from plant materials such as ferns; oil and natural gas are also formed largely from the remains of living things. The major deposits of fossil fuels being exploited today formed more than 100 million years ago, many times longer than humans have walked the Earth. Like all of today's living things, fossil fuels are the product of the food webs that begin with photosynthesis, the transformation of sunlight into chemicals useful for life. Fossil fuels are sunbeams from long ago.

The harnessing of fossil fuels is linked to the development of **thermodynamics**, the science of heat. Thermodynamics provided a conceptual framework for turning heat into work. The basic principle is a simple one: things expand when heated, and the burning of a fuel turns a solid, such as coal, or a fluid, such as natural gas or heating oil, into a hot gas. The hot gas pushes things, such as the blades of a fan (called a turbine when it is designed to be spun by hot gas) or the piston in a car engine. In this way, flame becomes force, and heat can be transformed, in part, into other, more useful forms of energy, such as the ones we find today in engines, computers, and air-conditioners. Turning burning oil into cool air from

BOX 7.2

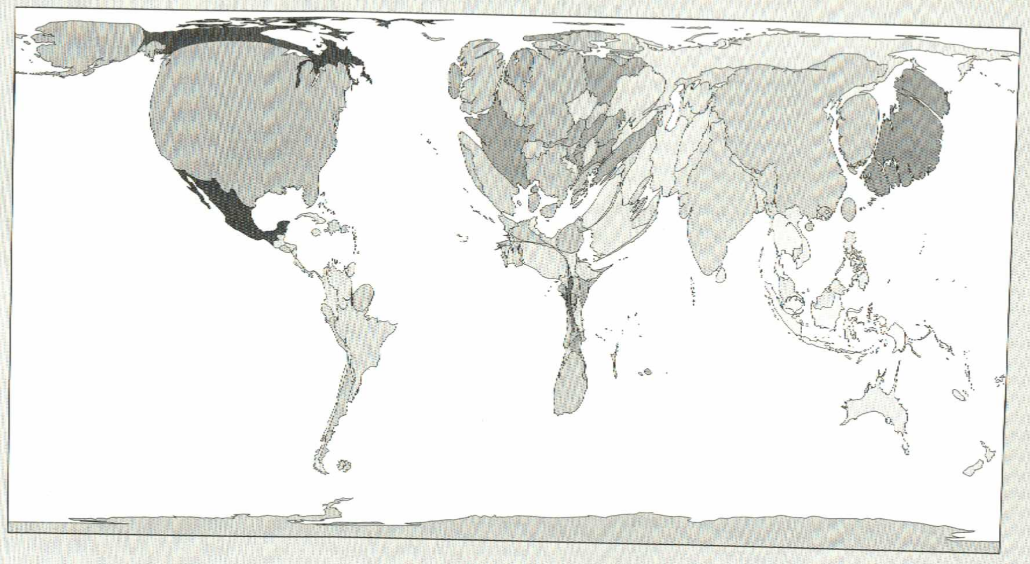
ENERGY AND PROSPERITY

One indicator of the basic connection between energy consumption and the economic circumstances of people may be seen in the cartogram below, which distorts the area of each of the world's countries in proportion to its fuel use.

In this map, the rich nations, including the United States, Japan, and the countries of the European Union, have areas much larger than they would have on a normal map. The poor countries, including most of sub-Saharan Africa and much of Latin America, appear shrunken.

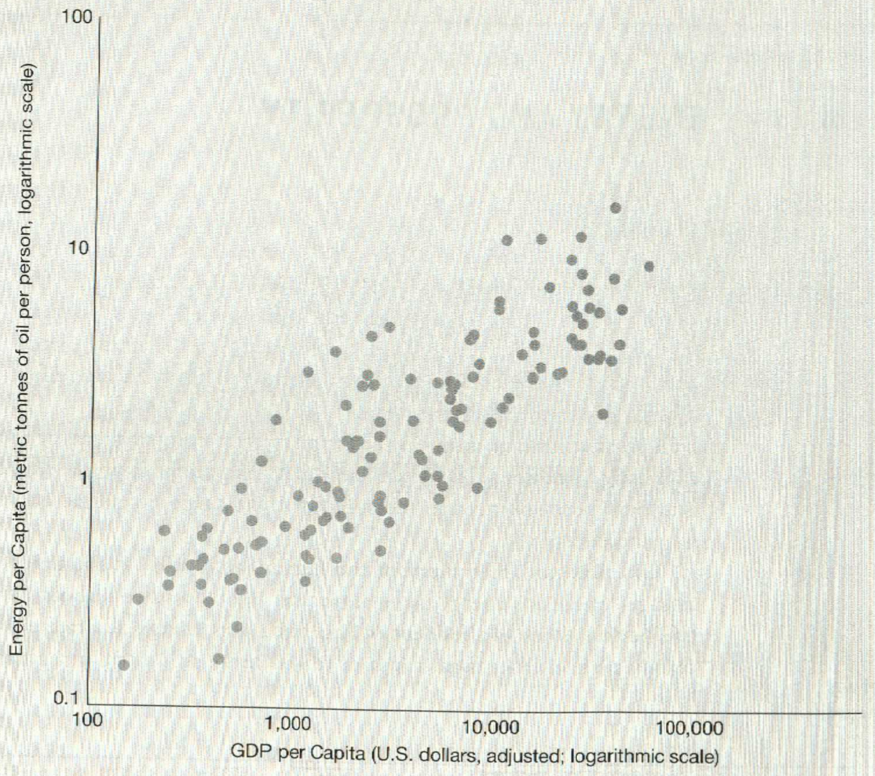
A similar point is made in the graph, which compares energy use to **gross domestic product (GDP) per capita**. As one might expect, a clear association is evident between income (measured by the average economic output per person) and energy use.

The biological machinery of the human body runs at about 100 watts. The average American's energy use—more than 10,000 watts—is about 100 times that of a person, whereas a resident of Argentina uses energy at a rate equal to about twenty people. One might think of this in terms of having (imaginary) "energy



Fuel use cartogram.

SOURCE: SASI GROUP (UNIVERSITY OF SHEFFIELD).



SOURCE: WORLD BANK.

Relationship between GDP and energy use, 2004.

servants." Americans have 5 times as many energy servants to do their bidding as Argentinians. Yet even in poverty-stricken Africa, energy from nonanimal sources is significant. Today, worldwide, 90 percent of that energy comes from fossil fuels.

The table also reminds us of something every visitor to a poor nation has experienced: someone in a rich country takes for granted many things, such as operating a washing machine, that are far from the experience of most people in a poor one.

Yet although a clear correlation exists between energy use and economic welfare, the association is not a rigid one. Japan has a GDP per person close to that of the United States, but a Japanese person uses energy at less than half the rate that an American does. The difference reflects in part the much larger size of the United States and our consequent use of more energy for transportation of goods and people. Another significant factor is differences in life-style. For example, most American residences are much larger than Japanese ones, and few Japanese houses are centrally heated. The differences among nations also suggest significant opportunities for lowering energy use that would not require decreases in health and well-being, though they would mean changes in life-style.

HUMAN-ENERGY EQUIVALENT OF TOTAL ENERGY CONSUMPTION, BASED ON AN AVERAGE HUMAN METABOLIC RATE OF 100 WATTS (APPROXIMATELY 2,000 CALORIES PER DAY, OR 3 MILLION BTU PER YEAR).

	Primary energy consumption, 2006 (million Btu/person)	"Energy servants" (1 human = 100 watts)
World	72.4	25
Africa	15.9	5
United States	334.6	115

Source: U.S. Energy Information Administration, International Energy Annual 2006, *Table E.1c (World Per Capita Total Primary Energy Consumption (Million Btu), 1980-2006), www.eia.doe.gov/iea/wecbtu.html.*

an air-conditioner sounds like magic, and if you think about it, so does the transformation of a lump of coal into megabytes of a music video flowing over the Internet. These examples, multiplied dozens of times in each person's day, are the result of the engineering knowledge built upon thermodynamics during the past two centuries.

Although the concepts of thermodynamics are used to control heat from all sources, the highest concentrations that could be tapped economically came from fossil fuels. It was only in the last third of the twentieth century that the even higher concentration of energy in uranium could be harnessed economically in commercial nuclear power. By then, coal, petroleum, and natural gas—burned in relatively simple furnaces or chambers such as the ones in the engine of a car—supplied more than 90 percent of the energy used in the world's richest nation.

This enormous array of technological capabilities made possible by harnessing energy led to the industrialization that dramatically increased material wealth in many economies (see Box 7.2: Energy and Prosperity, page 173). This connection can be directly visible. We can turn up the thermostat dial to warm our house in winter, enabling us to live in a cold climate through the consumption of energy.

Commuters feel the pinch of rising gasoline prices, reminding them how much they rely on affordable energy. A neglected power mower won't start, so a homeowner perspires behind a push mower to cut the grass—a reminder in another way of the gains we derive from energy.

These connections are also indirect: food in supermarkets has traveled, on average, more than a thousand miles from farm to shopping cart; nearly all plastics are manufactured from petroleum; and the more than one billion personal computers in the world depend on a reliable supply of electricity, including those that are portable. Some of these connections have significant environmental consequences: contaminated water in urban Africa can't be pumped or treated because of a lack of machines and reliable electric power; the mining of coal allows rainwater to percolate into rock crevices, forming acids and other pollutants that leach into streams, killing fish and sometimes whole ecosystems; the burning of fossil fuels releases gases into the atmosphere that are causing glaciers to melt and altering the chemistry of the oceans.

These examples could be multiplied many times over. Life in an industrialized economy such as Spain is obviously different in material terms from life in a developing country such as El Salvador. The differences can be traced in nearly every instance to the harnessing of energy.

ENERGY SOURCES

The energy we use comes from a variety of sources. As you can see in Figure 7.8, fossil fuel still provides about 85 percent of the energy used in the United States. Notice that the estimates of energy use in residential and commercial buildings, as well as in the industrial sector, exclude the consumption of electricity, which is reported separately. Of course, electricity is used almost entirely in industrial, residential, and commercial applications. The opportunities for generating and using electricity more efficiently are rather different, however, from those in the other three large end uses. All of those involve the direct harnessing of combustion, whereas electric energy is produced in turbines driven by hot gases—or by wind or falling water in a dam—and then distributed to end users.

Renewable energy sources, such as wind and hydropower, also draw energy indirectly from the Sun. As we discussed in Chapter 5, the heat of the Sun drives the weather, propelling wind and lifting water from the oceans up into the mountains through the precipitation cycle. Dams have been built on many streams to intercept the water flowing downhill in order to capture the water's energy to turn turbines.

Another renewable source is plant material. Wood has long been a major source of energy for humans, and today, crops are being grown and new crops are being developed to provide fuels to burn in engines and furnaces. To date, efforts to

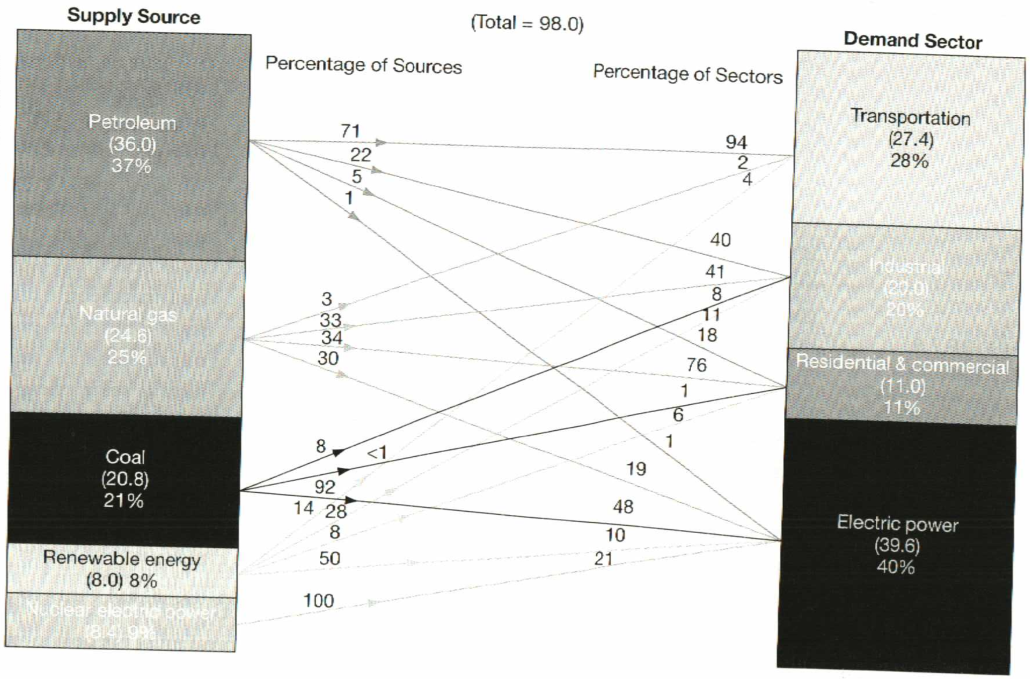


FIGURE 7.8 U.S. primary energy consumption, 2010. [Numbers in parentheses are in quadrillion Btu.]

SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION.

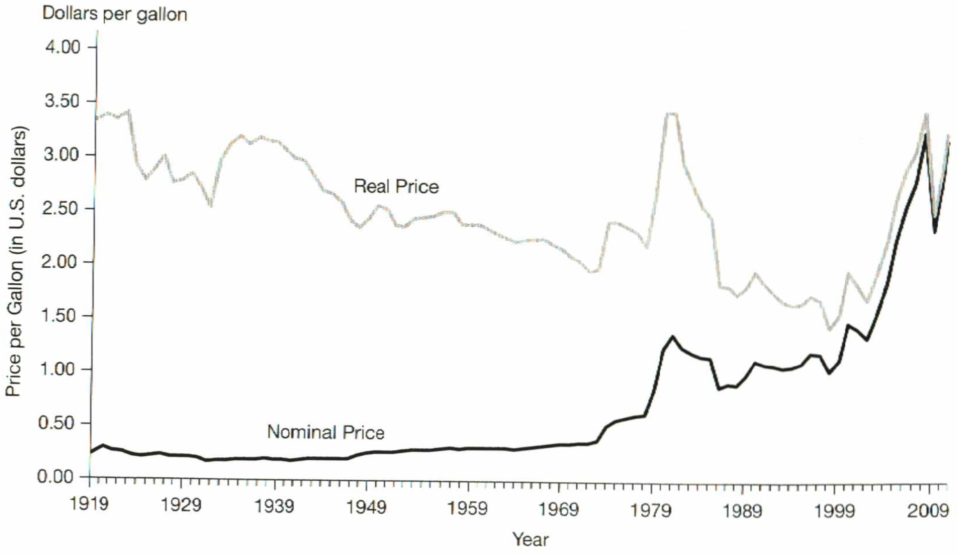
develop fuels from crops have suffered from significant problems, including the fact that growing crops can require substantial inputs of fossil fuels, but in the future, this may be a promising approach to developing renewable sources of liquid fuels for vehicles and aircraft. When plant materials are burned, they release carbon dioxide, but an equivalent amount was taken out of the atmosphere when the plant was growing, so the whole cycle should be roughly neutral in greenhouse gas emissions in favorable circumstances.

Sunlight can also be captured in photovoltaic cells—semiconductors somewhat like those in computer chips and flat-panel monitors—which convert light directly into electricity. Photovoltaic cells are expensive to manufacture, but the cost of production is being lowered enough that this approach may become competitive with more conventional approaches. The quantity of solar energy falling on Earth is roughly 10,000 times as large as total energy use by humans. The most efficient plants capture 3 to 10 percent of the sunlight falling on them, and the efficiency of photovoltaic cells can reach the low end of that range. From these numbers, one can see that, in principle, it would be possible to meet the world's energy needs not from ancient sunlight but from recent sunlight, using only renewable sources. One of the authors of this book, for example, installed photovoltaic panels on his roof, cutting his monthly electric bills by 99 percent; the initial cost was high, but with tax credits, the cost will be paid off in full in about twelve years. Still, the leap from a technology that can work in principle to one that becomes standard practice could be a long one for an economy built around inexpensive fossil fuels.

By far the most important fuel from an economic standpoint is petroleum. Changes in oil prices have tended to ripple through the markets for other fuels because oil can be used in residential, commercial, industrial, and transportation applications, and thus it competes against all other energy forms. As oil prices rise, other sources, including renewables, become more competitive economically. As you can see in Figure 7.9, the price of gasoline, the form of oil that people are most familiar with, has risen steeply over the past century. But if one takes out the effect of inflation, the cost of gasoline (and other forms of oil) actually fell over the course of that century. This has meant that alternatives such as solar energy have faced ever stiffer competition. This is the main reason fossil fuels remain dominant in the world's economies.

The most environmentally problematic fossil fuel is coal. Coal is mostly carbon, and when it is burned, it releases the most carbon dioxide of any fuel per unit of useful energy. So coal contributes more to climate change, proportionally, than other fuels. In addition, the impurities in coal are harmful to people and the environment. Coal often contains significant quantities of sulfur. When burned, the result is sulfur dioxide, a major contributor to health-threatening air pollution.

FIGURE 7.9
U.S. gasoline prices since cars became popular. The nominal price is the price charged at the pump; the real price is adjusted for inflation using the consumer price index through January 2012.



SOURCE: U.S. ENERGY INFORMATION ADMINISTRATION

Coal also contains trace impurities such as mercury, and coal-fired electric power plants are a major source of the mercury generated by human activities. Mercury is a potent neurotoxin that can affect the development of children's brains. But coal is more abundant than any other fossil fuel. The world's largest reserves are in China, where electric power plant construction proceeds at a rapid pace to meet the demands of an industrializing economy.

There is one major alternative to fossil fuels that many environmentalists don't like to talk about—nuclear power. In routine operations, nuclear power plants are cleaner than fossil-fired ones per unit of energy produced. Nuclear plants emit no CO_2 because the steam they use to spin turbines comes from splitting uranium or plutonium nuclei to boil water. Atomic power also emits very little air pollution. Indeed, because of the impurities in coal, a properly operating nuclear power plant actually emits less radiation than an average coal-fired plant. Today, more than one hundred nuclear plants supply about one-fifth of the electricity used in the United States. France, the world leader in nuclear energy development, generates about four-fifths of its electricity from atomic energy.

As with every form of energy, however, nuclear power has risks, which were dramatically illustrated during the 2011 disaster in Japan. Although the Fukushima nuclear complex meltdowns were caused by a magnitude 9.0 earthquake and tsunami that was larger than had occurred in the recent past, the accident revealed frailties in the design of the whole system. Engineers had warned that an earthquake of this magnitude was reasonably likely to occur and that the reactors and spent-fuel storage systems were not designed to withstand such an event. Those particular problems will now be taken into account, but it is likely that other severe nuclear accidents—due to issues that are as yet unknown—will occur, just as plane crashes persist despite increasing improvements in safety and training. Worry about these risks led the German government to embark on a phaseout of nuclear energy in that country in 2011. This is having the ironic effect of increasing Europe's emissions of greenhouse gases, even though some European countries, including Germany, have been converting to renewable sources such as wind power far more rapidly than the United States.

An unresolved environmental concern of nuclear energy is waste disposal. When the nuclei of uranium or plutonium undergo fission, highly radioactive nuclear fragments are produced. The fission process also generates substantial quantities of other material that becomes mixed with and contaminated by radioactive elements. Although most of the radioactive elements decay rapidly, some long-lived radioactive constituents pose substantial biological hazards. These must be isolated for long periods—in some cases, for thousands of years. The geoscientists and engineers who have studied nuclear waste disposal think this is not an insoluble problem, and a number of designs with layers of safety features have been developed in prototype. But assuring the survival of human institutions to take care of these waste-isolation facilities for thousands of years is impossible, and controversy continues over how to seal and abandon a waste repository safely.

In addition to waste, making the fuel for nuclear power plants is a process that overlaps with the creation of ingredients needed for nuclear weapons. Trying to slow the proliferation of nuclear weapons while more nations clamor for nuclear power has proved to be a thorny political problem.

Asian economies are now leading the way with a new generation of nuclear power plants, so today's students will get to see how reliable they are. There may well be additional pressure to develop nuclear power as a way to generate electricity with fewer greenhouse gas emissions. But the cost of building and operating nuclear plants is high, and this factor may determine how many are built. In any case, the choices in coming decades will likely not be controlled by the critics of nuclear power, who have, for better or worse, played a key role in stalling the nuclear option for a generation.

The largest and least costly "supply" of clean energy is conservation. Technical improvements, such as better-insulated buildings, combined with smarter use of energy will give us more of what we want with less generation of greenhouse gases and other pollutants. **Energy efficiency** is a large but fuzzy resource, because estimating the technological potential for more efficient energy use is only a crude measure of what can be achieved practically; most estimates of technological potential suggest that 10 to 50 percent of U.S. energy use could be rechanneled into more efficient patterns.

Efficiency is not free, and installing and using more efficient methods can require some behavioral adaptations, such as learning how to install weather stripping around the edge of a drafty window. This is not hard and the friendly staff at your local hardware store will be glad to show you how. The problem lies in the number of windows and doors that need to be weatherstripped for the full potential of that particular improvement to be captured. There are literally millions of them, and most are in private dwellings whose occupants don't like the idea of energy inspectors dropping by. This is a social barrier, not a technological one, but it is not easily hurdled.

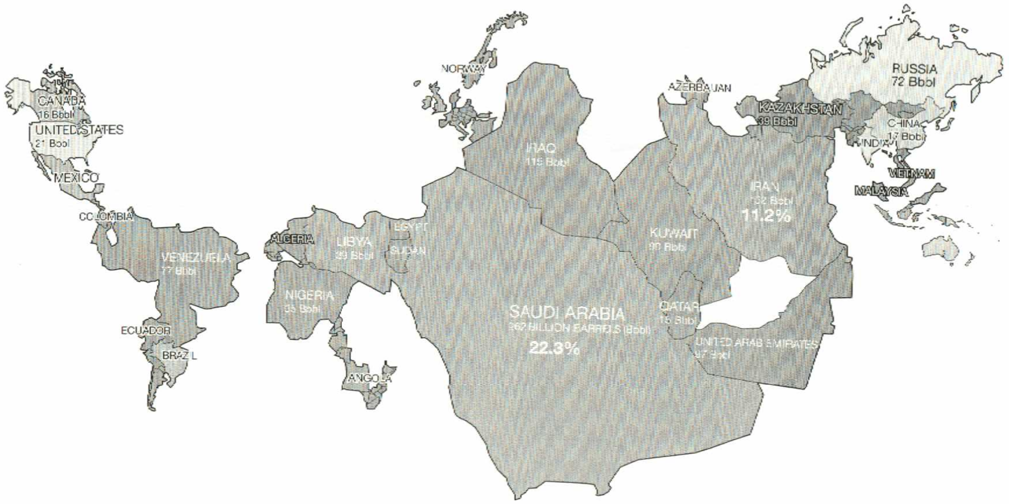
One way around the barrier is higher energy prices. If the cost of heating oil skyrockets, homeowners will have reason to economize on fuel. Greater energy efficiency is one way to do that while maintaining the warmth of a home during a cold winter. Higher prices, together with programs by utility companies and government agencies, have made significant contributions over the past generation. Another approach is to require more efficient technology in new buildings and in renovated ones. This can be done by provisions of building codes administered by local governments and followed by builders. Tighter windows, more insulation in walls, and other measures have gradually made their way into new and upgraded structures. Mileage standards for new cars provide a similar approach to raising energy efficiency. There is a long way yet to go, however, in the sense that energy users can still reduce their consumption substantially while saving money, even taking into account the cost of more efficient technology. We return to this question below, when we discuss international action to respond to climate change.

ENERGY AND THE WORLD WITHOUT EDGES

Energy resources are not distributed evenly throughout the world. Figures 7.10 and 7.11 provide a graphic demonstration of disproportionality in the ownership of petroleum. This fact has profound political and economic implications (see Box 7.3: Geology, Economics, and Politics, page 182).

Oil is a finite resource. As with all fossil fuels, oil is not being produced at a significant rate in the natural world. All the fossil fuels we pump, mine, and burn now may eventually be resupplied through natural processes, but these will take millions of years. Wood, by contrast, regrows fast enough that forests in the United States actually increased in area during the twentieth century. Sunlight pours in each day. It is accordingly relevant to ask how much of the different fossil fuels is available and how long we might be able to use them, particularly as they form the basis of the material comforts and the economy that we now have.

FIGURE 7.10
World oil reserves by country (cartogram). The total reserves for the top fourteen oil-producing nations are given in billions of barrels (Bbbl) and as a percentage of the world's reserves.



SOURCE: ENVIRONMENTAL ACTION.

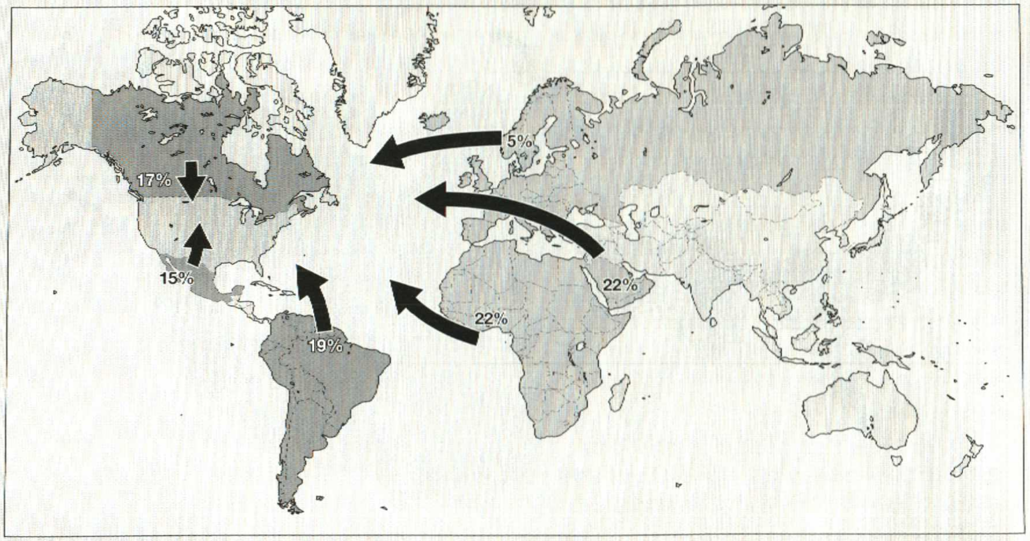
BOX 7.3

GEOLOGY, ECONOMICS, AND POLITICS

The cartograms in the "Energy and Prosperity" box and in Figure 7.10 show energy use and the distribution of energy resources, respectively, and they are strikingly different in appearance. That is, the places where the most energy is used are not the same as where it is produced. The figure below shows where oil imported into the United States comes from. Although well more than a third comes from Canada, Mexico, and western Europe, almost two-thirds comes from South America, western Africa, and the Middle East. America's principal allies in Europe and Japan are even more heavily dependent on imports of fossil fuels, with Russia supplying nearly all of the natural gas burned in Europe, as well as a large fraction of the oil.

The other major oil-producing countries include Venezuela; Nigeria and Angola in Africa; and Saudi Arabia, Iraq, and Iran in the Middle East. Each of these countries is a focus of intense concern. Several have been politically unstable, including Nigeria, Angola, and Iraq. Iran and Venezuela have been highly critical of America and its allies, and Russia and the United States have had a nervous and ambivalent political relationship since the Cold War ended in the 1990s. U.S.

U.S. oil imports, monthly average, June 2005 to November 2006.



SOURCE: LUGAR ENERGY INITIATIVE, CITING DATA FROM U.S. ENERGY INFORMATION ADMINISTRATION.