Civilization as a Global Geosystem 13

Learning Objectives

Human population and the energy needed to sustain this population are multiplying at phenomenal rates. This chapter contains the essential facts and figures that you will need to:

13.1 Explain how the impact of civilization on the Earth system qualifies it as a global geosystem.

13.2 Categorize our natural resources as renewable and nonrenewable, and differentiate energy reserves from energy resources.

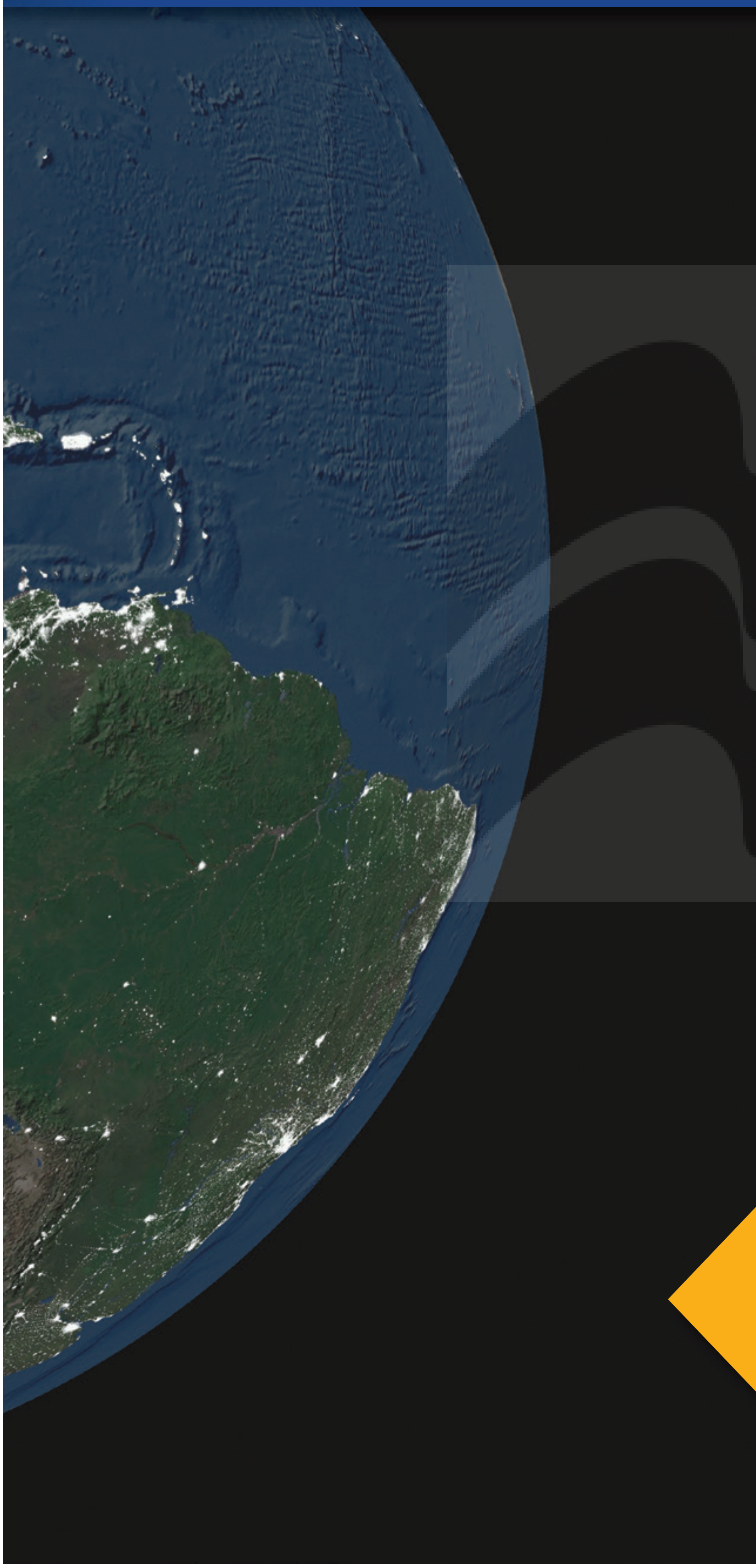
13.3 Understand the geological processes that form fossil fuels and the energy available from their reserves.

13.4 Answer the question: When will civilization run out of oil?

13.5 Compute the carbon intensities of fossil fuels from the energy they produce and the carbon dioxide they emit, and use carbon intensities to compute the changes in carbon flux from changes in energy production.

13.6 Quantify the relative contributions of alternative energy resources to energy production, and estimate their potential to satisfy future energy needs.

13.7 Project the worldwide growth of energy consumption by geographic region and fuel type.



North and South America at night, showing the lights of our globalized, energy-intensive civilization. [Image by NOAA's National Geophysical Data Center from data collected by US Air Force Weather Agency.]

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A better understanding of the Earth system has helped us find natural resources, sustain the natural environment, and reduce the risks from natural hazards. But the upward progress of our civilization cannot be taken for granted. The human population is growing at a phenomenal rate, and Earth's natural resources are limited. Environmental conditions and overall prosperity are not improving in some parts of the world, and the prospects for detrimental changes to the global environment loom large. Balancing the benefits we reap from our use of natural resources against the costs of that use—particularly harmful long-term changes to our environment—raises new challenges for Earth science and society.

In this chapter, we show how civilization—the collective sum of human activities—has grown into a global geosystem that is changing Earth's surface environment at a phenomenal rate. We survey the energy resources that fuel our economy and examine how our future use of those resources will affect our environment. We focus on two of civilization's most pressing problems: the need for more energy resources to power economic development and the potential for energy usage to cause detrimental global change.

Our economy depends on the burning of nonrenewable energy resources (fossil fuels) that produce a dangerous greenhouse gas (carbon dioxide). This stark reality poses some difficult questions: How long will our fossil-fuel resources last? How quickly is fossil-fuel burning increasing greenhouse gases in the atmosphere, and how will those increases change the climate system? How quickly will we need to replace fossil fuels with alternative energy sources to sustain our economy and environment? These questions have political and economic dimensions that extend far beyond Earth science, so they do not have strictly scientific answers. Nevertheless, the decisions we will make as a society must be informed by our best scientific predictions about how the Earth system will change over the next decades and centuries. Realistic predictions about the future global environment can be made only if we include civilization as part of the Earth system.

Growth and Impact of Civilization

The human habitat is the thin, water-rich interface where Earth meets sky, where three global geosystems—the climate system, plate tectonics, and the geodynamo—interact to provide a life-sustaining environment. We have increased our standard of living by developing technologies that can ever more efficiently exploit this environment: grow more food, extract more minerals, transport more materials, build more structures, and manufacture more goods of all kinds. One result has been an explosion in the human population.

Human Population Growth

Early in the Holocene, about 10,000 years ago, when the climate was warming and agriculture first began to flourish, roughly 100 million people were living on the planet. Population grew slowly (Figure 13.1). The first doubling, to 200 million, was achieved early in the Bronze Age, about 5000 years ago, when humans first learned how to mine ores and refine them into metals such as copper and tin (of which bronze is an alloy). The second doubling, to 400 million, was not achieved until the Middle Ages, about 700 years ago. But once industrialization began in the late eighteenth century, the global population really took off, climbing to 1 billion in about 1800, 2 billion in 1927, and 4 billion in 1974. By the mid-twentieth century, the doubling time for the human population had dropped to only 47 years—less than a human lifetime. The world population exceeded 7 billion in early 2012, and, although its growth rate is expected to decline, the total will almost surely top 8 billion by 2030.

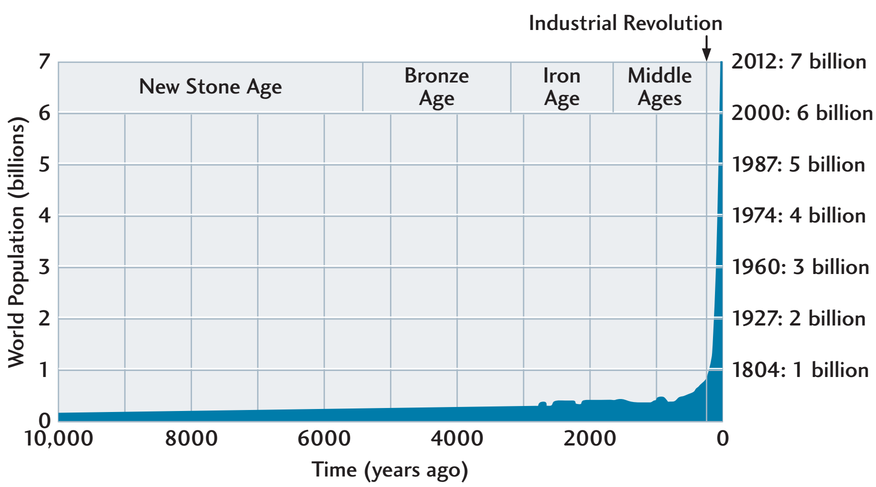


FIGURE 13.1 Human population growth over the last 10,000 years. The global population is expected to reach 8 billion by 2028. [Data from the U.S. Census Bureau.]

As our population has exploded, the demand for natural resources has skyrocketed. Our energy usage has risen 1000 percent over the last 70 years and is now increasing twice as fast as the human population. The view of Earth from space in this chapter's opening photograph shows a glowing lattice of highly energized urbanization spreading rapidly across the planet's surface.

Human activities have altered the environment by deforestation, agriculture, and other land-use changes since civilization began. But in earlier times, the effects of our species, *Homo sapiens,* were usually restricted to local or regional habitats. Today, industrialized energy production makes it possible for civilization to compete with the climate system and plate tectonics in modifying Earth's surface environment. The global scale of these modifications can be illustrated by some startling observations:

- Human activities are currently eroding the land surface 10 times faster than all natural processes combined.
- Since the beginning of the Industrial Revolution, humans have increased the sediment load of the world's rivers by almost 30 percent. Dams and reservoirs built by humans now trap almost 40 percent of this global sediment load before it reaches the oceans.
- In the last century, humans have converted about one-third of the world's forested area to other land uses, primarily agriculture.
- Within 50 years after the invention of the artificial coolant freon, enough of it had leaked out of refrigerators and air conditioners and floated into the upper atmosphere to damage Earth's protective ozone layer.
- Burning of fossil fuels has increased the concentration of carbon dioxide in the atmosphere by almost 50 percent over preindustrial levels.

We are not just part of the Earth system; we are transforming how the Earth system works, perhaps in fundamental ways. In the blink of a geologic eye, civilization has developed into a full-fledged global geosystem.

Energy Resources

Energy is required to do work; hence, access to energy is fundamental to all aspects of civilization, including population growth. **Energy resources** refer to the total energy that civilization could potentially produce from the natural environment. A century and a half ago, most of civilization's available energy was produced by burning wood (Figure 13.2). A wood fire, in chemical terms, is the combustion of *biomass,* organic matter consisting of carbon and hydrogen compounds, or **hydrocarbons.** Biomass is produced by plants and animals in a food web based on photosynthesis. Thus, the ultimate source of the energy in wood is the sunlight plants use to convert carbon dioxide and water into hydrocarbons. Combustion of wood or other biomass produces heat energy and returns carbon dioxide and water to the environment. In this capacity, the biomass acts as a short-term reservoir for storing solar energy. Biomass is a **renewable resource** because the biosphere is constantly producing new hydrocarbons. Before the mid-nineteenth century, the burning of wood and other biomass derived from plants and animals (e.g., whale oil, dried buffalo dung) satisfied most of society's need for fuel. Today, the energy derived from biomass is only a small share of our total

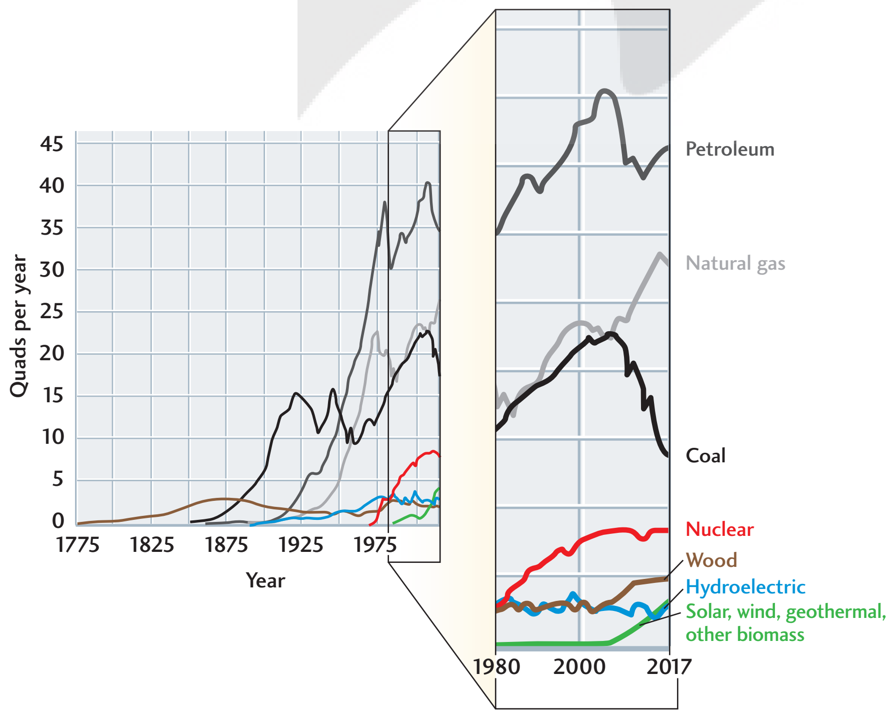


FIGURE 13.2 U.S. energy consumption, shown here for the period 1775–2017, has successively been dominated by the burning of wood, coal, and oil. In just the past few years, the energy from coal has dropped while that from natural gas and renewable sources such as biomass, solar, and wind has increased. Here and elsewhere in this chapter, the energy units are quads per year (1 quad = 10^{15} Btu = 1.054×10^{18} J). [Data from U.S. Energy Information Agency.]

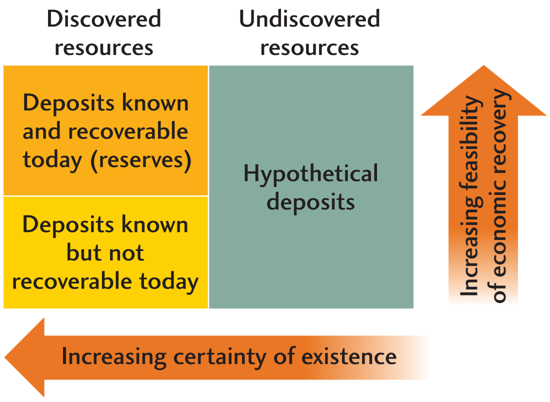


FIGURE 13.3 Fossil-fuel resources include reserves, plus known but currently unrecoverable deposits, plus undiscovered deposits that geologists think may eventually be found.

energy usage, though that fraction is now increasing owing to the industrial production of ethanol and other biofuels.

Coal, a combustible rock, was formed from biomass that was buried in sedimentary rock formations millions of years ago, particularly during the Carboniferous period. When we burn coal, we are using energy stored from Paleozoic sunlight. Hence, the primary source of this fossilized energy is the same solar power that drives the climate system. Our other major fuels, crude oil (petroleum) and natural gas (methane), are also created from dead organic matter. Coal, oil, and natural gas are hydrocarbon-rich substances known collectively as **fossil fuels.** Fossil-fuel resources are the entire supply of fossil fuels in the lithosphere that may become available for human use in the future. Geologists use a more restrictive term, **reserves,** to describe proven deposits that can be exploited economically (and legally) at the present time. Resources are more uncertain "guesstimates" that include reserves plus known but currently unrecoverable supplies plus undiscovered supplies that are likely be found sometime in the future (Figure 13.3). At current rates of use, our fossil-fuel reserves will be exhausted long before geologic processes can replenish them; therefore, they are **nonrenewable resources.**

Rise of the Hydrocarbon Economy

Civilization has used a variety of renewable energy sources to power mills and other machinery for thousands of years, including wind, falling water, and the work of horses, oxen, and elephants. By the late eighteenth century, however, industrialization was increasing the demand for energy beyond what these traditional renewable sources could supply. About 1780, James Watt and others developed coal-fired steam engines that could do the work of hundreds of horses, sparking the Industrial Revolution. Steam technology lowered the price of energy dramatically, in part because it made coal mining possible on an industrial scale. By the end of the nineteenth century, coal accounted for more than 60 percent of the U.S. energy supply (see Figure 13.2).

The first oil well was drilled in Pennsylvania by Colonel Edwin L. Drake in 1859. The idea that petroleum could be profitably mined like coal provoked skeptics to call the project "Drake's Folly" (Figure 13.4). They were wrong, of course. By the early twentieth century, oil and natural gas

FIGURE 13.4 Edwin L. Drake (*right*) in front of the oil well that initiated the "age of petroleum." This photo was taken by John Mather in 1866 in Titusville, Pennsylvania. [Bettmann/Getty Images.]

were beginning to displace coal as the fuels of choice. Not only did they burn more cleanly than coal, producing no ash, but they could be transported by pipeline as well as by rail and ship. Moreover, gasoline and diesel fuels refined from crude oil were suitable for burning in the newly invented internal combustion engine.

Today, the engine of civilization runs primarily on fossil fuels. Taken together, oil, natural gas, and coal account for 81 percent of global energy consumption. We can fairly call the civilization fed by this energy system a **hydrocarbon economy**: one that takes hydrocarbons stored in the lithosphere and burns them in the atmosphere to produce the energy that humans require. This burning also produces waste materials that humans must either bury in the lithosphere or release into the environment. Essentially all of the carbon dioxide produced by fossil-fuel burning is released into the atmosphere.

To understand the implications, we will undertake an accounting of our energy usage in terms of the carbon dioxide it produces, comparing fossil fuels with alternative sources of energy. This accounting requires a careful estimation of how much carbon dioxide is produced by each unit of energy captured during the burning of a fuel, a ratio called the **carbon intensity** (see the Practicing Geology Exercise at the end of the next section).

Energy Consumption

Energy use is often measured in units appropriate to the fuel—for example, barrels of oil, cubic feet of natural gas, and tons of coal. But comparisons are much easier if we express fuel consumption in terms of its *equivalent energy,* the amount of energy the fuel produces on burning. A popular choice for measuring equivalent energy is the British thermal unit (Btu). One Btu is the amount of energy needed to raise the temperature of 1 pound of water by 1°F (1055 joules). When we measure large quantities, such as a nation's annual energy use, we use units of 1 quadrillion (10^{15}) Btu, or **quads.** One quad (1.055×10^{18} joules) is a huge amount of energy, equivalent to burning 170 million barrels of oil, 970 billion cubic feet of natural gas, or 36 million tons of coal.

Energy production of the United States in 2015 was about 97.7 quads of energy (Figure 13.5), compared with a global total of 536 quads. Thus, the United States, with 4.4 percent of the world's population, consumes about four times more energy per person (or *per capita*) than the

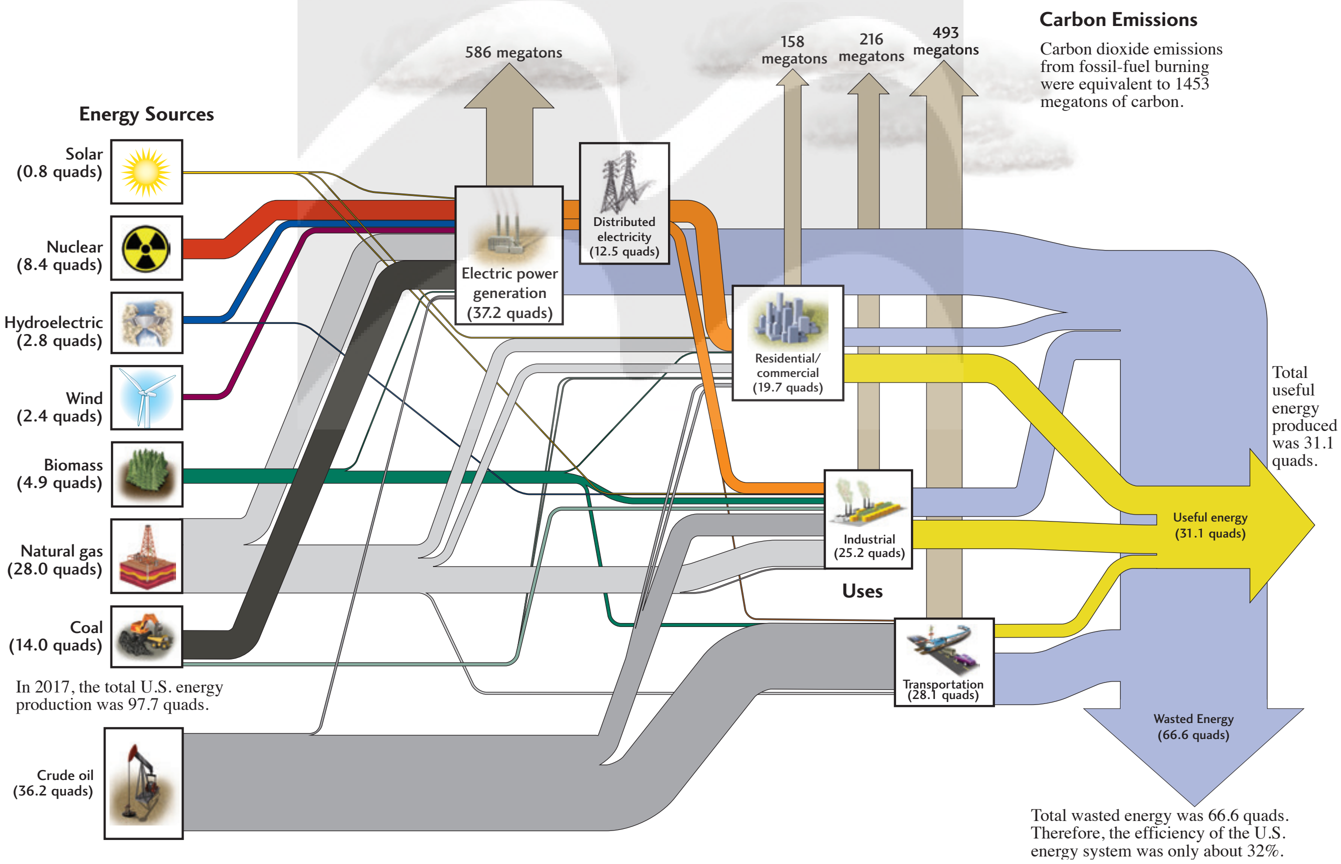


FIGURE 13.5 Energy consumption in the United States in 2017 (in quads). Energy from primary fuel sources (boxes on left side) is delivered to the residential, commercial, industrial, and transportation sectors (boxes in middle to right side). Not represented are small contributions to electric power generation from geothermal energy (0.2 quad). [Information from Lawrence Livermore National Laboratory, based on data from the Energy Information Administration.]

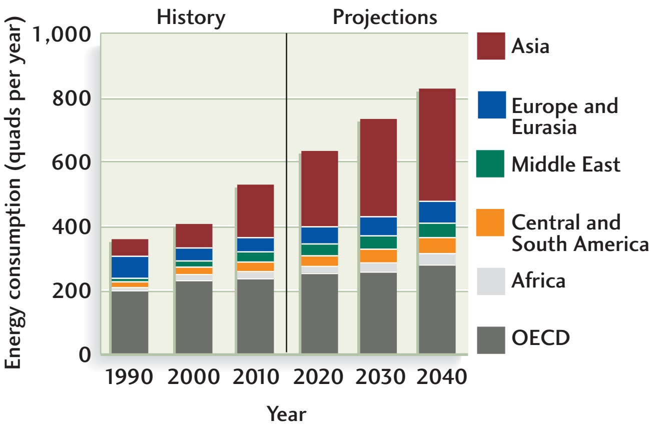


FIGURE 13.6 Historical and projected energy consumption in quads per year by world regional groupings, 1990–2040. The Organization for Economic Cooperation and Development (OECD) includes countries in Western Europe, North America, and Australia. About 70 percent of the growth in energy consumption will come from developing nations outside the OECD. [Data from the U.S. Energy Information Agency, 2015.]

global average. Fossil fuels provided 80 percent of that total, nuclear power 9 percent, and renewable energy sources 11 percent. You will notice that the flow of energy through the U.S. energy system is not particularly efficient: About 32 percent of the energy performs useful work, while 68 percent is wasted.

There are promising signs that new energy-efficient technologies and increasing energy conservation are beginning to lessen U.S. energy appetites. In fact, the total annual U.S. consumption of energy of all types dropped by 3.7 percent between 2007 and 2017, the first multiyear drop in recent history. On a global basis, however, modest reductions in energy consumption by the United States, Japan, and Western Europe have been more than offset by increases in the developing world, led by the world's two most populous countries, China with 4 percent per year average energy growth since 2007 and India with 5 percent per year. Even with its high growth rates, China's per capita energy use is still 3 times less than the United States, owing to its much larger population. As China and other developing economies strive to improve their standards of living, global energy use per capita is bound to rise, accelerating overall energy consumption. Global annual energy consumption is projected to exceed 600 quads by 2020 (Figure 13.6).

Carbon Flux from Energy Production

In the prehuman world, the exchange of carbon between the lithosphere and the other components of the Earth system was regulated by the slow rates at which geologic processes buried and unearthed organic matter. This natural carbon cycle has been disrupted by the rise of the hydrocarbon economy, which is now pumping huge amounts of carbon from the lithosphere directly into the atmosphere. In Figure 13.5, you can see that the U.S. energy system released about 1.5 gigatons (Gt) of carbon into the atmosphere in 2017, primarily as CO_2 (1 Gt = 1 billion metric tons = 10^{12} kg). Over the decade 2000–2009, the total global emissions from fossil-fuel burning averaged 7.8 Gt per year, but this mass has increased to about 10 Gt per year in 2018.

As we saw in Chapter 12, the climate system is tightly coupled to the global carbon cycle because carbon dioxide is a greenhouse gas. The concentration of this gas has risen rapidly from its preindustrial level of about 280 ppm to over 410 ppm today. If the burning of fossil fuels continues unabated, the amount of CO_2 in the atmosphere will double its preindustrial level by mid-century.

Anthropogenic increases in carbon dioxide and other greenhouse gases have already led to enhancement of the greenhouse effect and global climate warming. It is clear that the future of the climate system and its living component, the biosphere, depends on how our society manages its energy resources, which we will now consider in more detail.

Fossil-Fuel Resources

How much do we need to worry about depletion of our nonrenewable energy resources? The world's proven reserves of fossil fuels sum up to about 53,000 quads (Figure 13.7), which is almost a hundred times greater than the world's annual consumption (536 quads per year in 2017). Discoveries of new resources, as well as more advanced technologies for extracting fossil fuels, will add substantially to these reserves. In the case of petroleum, for example, the resources available for exploitation over the

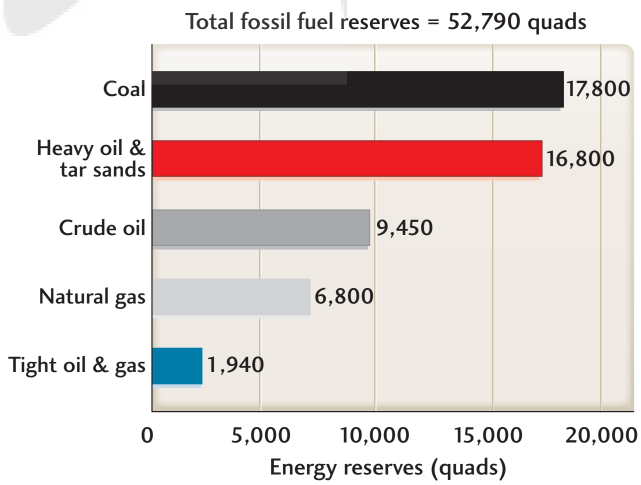


FIGURE 13.7 Estimates of total fossil-fuel energy reserves amount to about 53,000 quads. The total fossil-fuel resources that could be recovered with improved technologies and lower costs are at least four times this amount. [Data from the World Energy Council.]

next century are estimated to be two to three times the current reserves. Hence, hydrocarbon resources will no doubt be available to power civilization for many decades to come. A number of factors complicate the economics of energy production, including the environmental costs of fossil-fuel burning and the increasing availability of renewable energy resources. In this section, we describe how fossil fuels are formed by geological processes, and we take stock of our current reserves.

The Geologic Formation of Hydrocarbons

Economically valuable deposits of hydrocarbons develop under special geologic conditions. Fossil fuels come from the organic debris of former life: plants, algae, bacteria, and other organisms that have been buried, transformed, and preserved in sediments.

Coal is a biological sediment formed from large accumulations of plant material in wetlands where plant growth is very rapid (**Figure 13.8**). Burial in waterlogged soil preserves the plant material by cutting it off from the oxygen needed for bacterial decay. As the plant material accumulates, it turns into *peat*, a porous brown mass of organic matter in which leaves, twigs, roots, and other plant parts can still be recognized. The accumulation of peat in oxygen-poor environments can be seen in modern swamps and peat bogs. When dried, peat burns readily because it contains up to 50 percent carbon.

Chemical reactions during compression and heating of the organic-rich sediments (diagenesis) can convert peat first to *lignite*, a very soft, brown coal containing 60–70 percent carbon and then to *bituminous* coal that contains up to 80 percent carbon. At still higher temperatures and pressures, low-grade metamorphic reactions transform soft coal to hard coal, or *anthracite*, which contains more than 90 percent carbon, further increasing its energy content.

Liquid and gaseous hydrocarbon fuels also begin to form in sedimentary basins where the production of organic

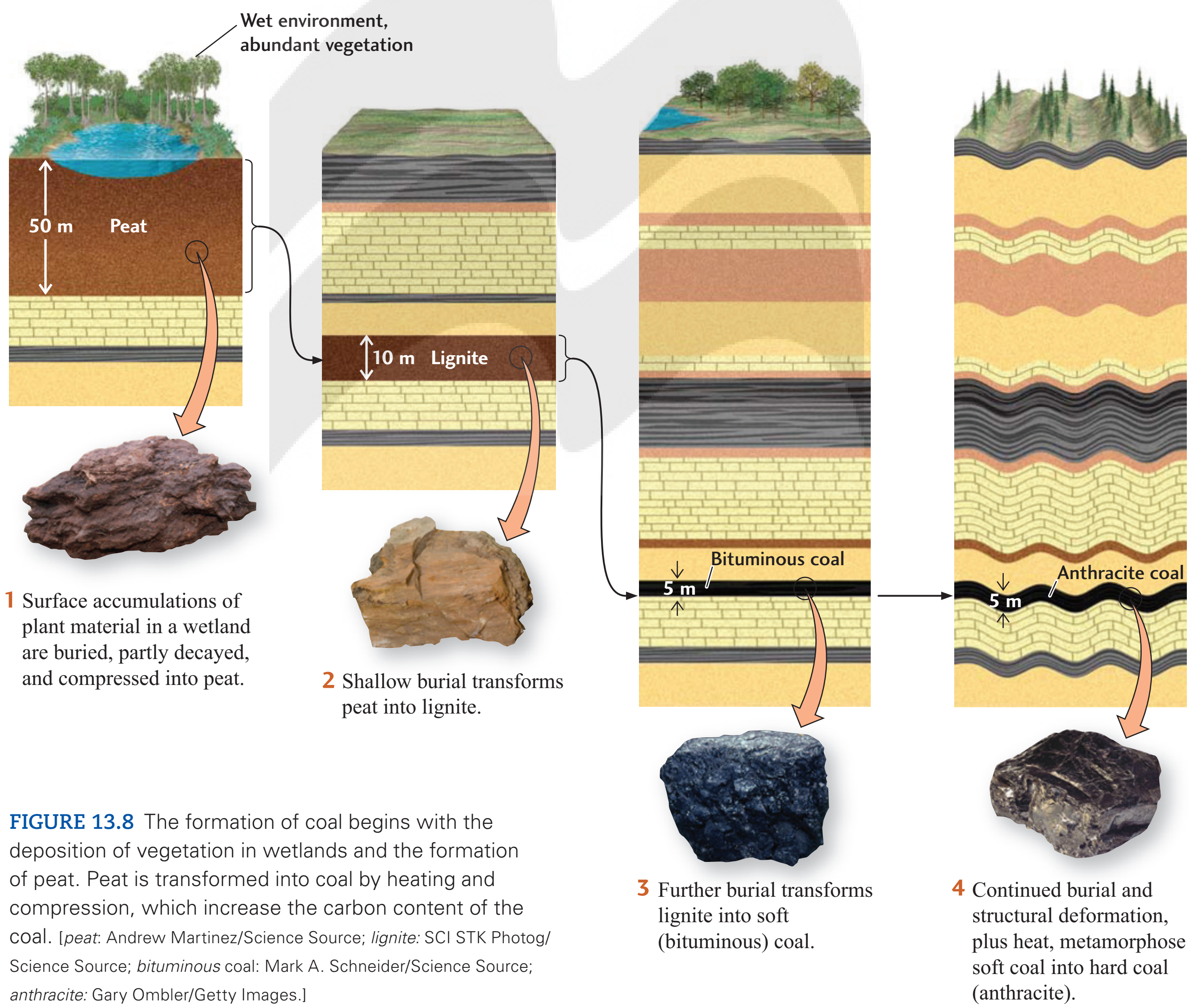


FIGURE 13.8 The formation of coal begins with the deposition of vegetation in wetlands and the formation of peat. Peat is transformed into coal by heating and compression, which increase the carbon content of the coal. [*peat*: Andrew Martinez/Science Source; *lignite:* SCI STK Photog/Science Source; *bituminous* coal: Mark A. Schneider/Science Source; *anthracite:* Gary Ombler/Getty Images.]

matter is high and the supply of oxygen in the sediments is inadequate to decompose much of the organic matter they contain. Many offshore thermal subsidence basins on continental margins satisfy these two conditions, as do some river deltas and inland seas. During millions of years of burial, diagenetic reactions at elevated temperatures and pressures slowly transform the organic material in these *source beds* into combustible hydrocarbons. The simplest hydrocarbon is methane (CH_4), the primary constituent of **natural gas.** Raw petroleum, or **crude oil,** includes a diverse class of liquids composed of more complex hydrocarbons.

Crude oil forms at a limited range of pressures and temperatures, known as the **oil window,** usually found at depths between about 2 and 5 km (see the Chapter 6 Practicing Geology Exercise, *Where Do We Look for Oil and Gas?*). Above the oil window, temperatures are too low (generally below 50°C) for the maturation of organic material into hydrocarbons, whereas below the oil window, temperatures are so high (greater than 150°C) that the hydrocarbons that form are broken down into methane, producing natural gas.

Hydrocarbon Reservoirs

As sediment burial progresses, compaction of the source beds forces crude oil and natural gas into adjacent beds of permeable rock, such as sandstones or fractured limestones, which act as *hydrocarbon reservoirs*. The relatively low densities of oil and gas cause them to rise, so that they float atop the water that almost always occupies the pores of permeable rock formations. The conditions that favor large-scale accumulation of oil and natural gas are where permeable geologic formations are capped by layers of impermeable rock, such as shales or evaporites. This barrier to upward migration forms an **oil trap** (Figure 13.9).

Some oil traps, called *structural traps*, are created by rock deformation. One type of structural trap is formed by an anticline in which an impermeable layer of shale overlies a permeable sandstone formation (Figure 13.9a). The oil and gas accumulate at the crest of the anticline—the gas highest, the oil next—both floating on the groundwater that saturates the sandstone. Similarly, an angular unconformity or displacement across a fault may place a dipping permeable limestone formation opposite an impermeable

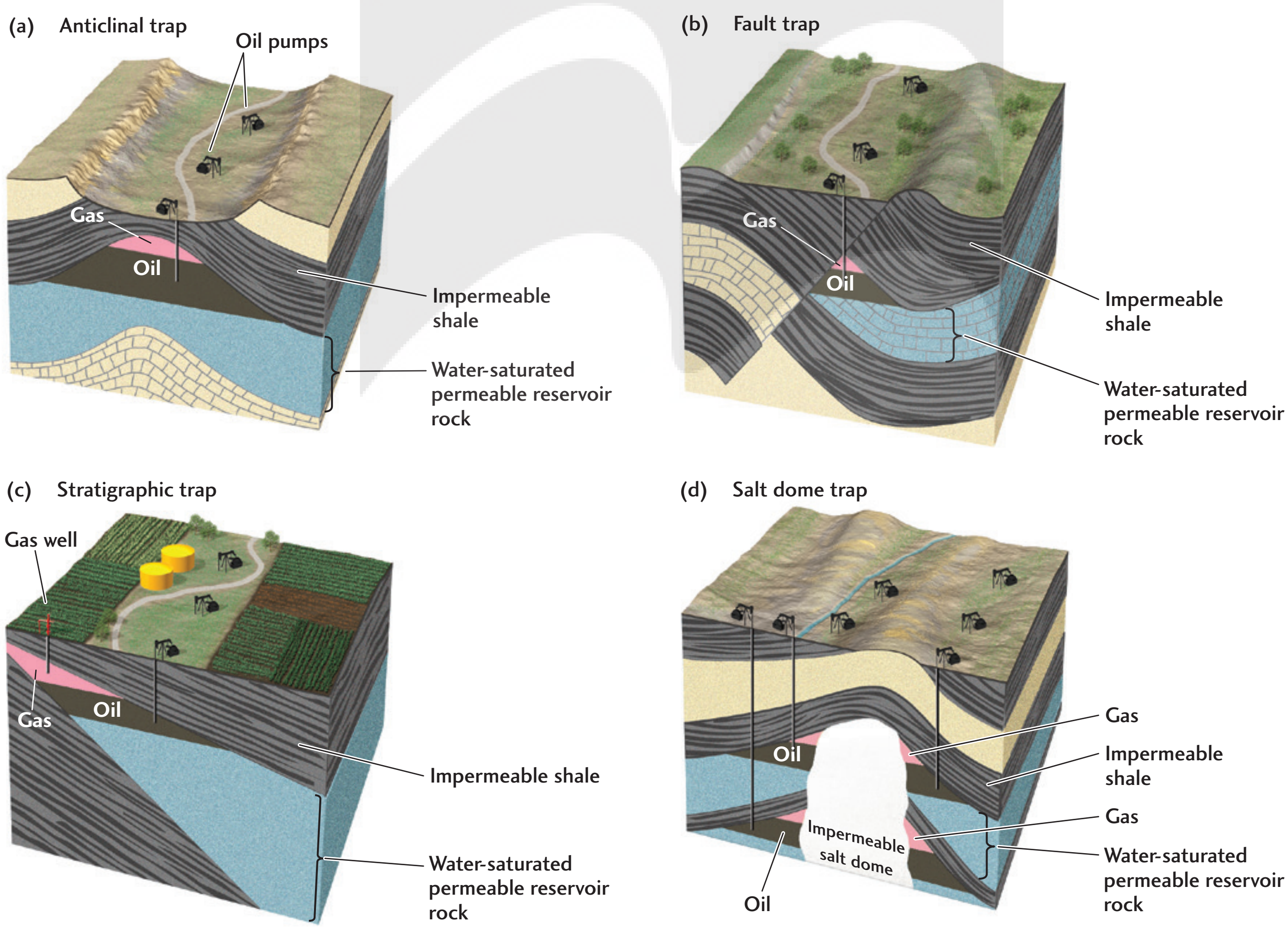


FIGURE 13.9 Oil and gas accumulate in traps formed by geologic structures. Four types of oil traps are illustrated here.

FIGURE 13.10 New technologies used aboard offshore platforms in the Gulf of Mexico can recover oil and gas from rock reservoirs below very deep waters. Drilling from a single platform like this one can cost over $100 million. [Larry Lee Photography/Getty Images.]

shale, creating another type of structural trap (Figure 13.9b). Other types of oil traps are created by the original pattern of sedimentation, such as when a dipping permeable sandstone formation thins out against an impermeable shale (Figure 13.9c). These structures are called *stratigraphic traps*. Oil can also be confined against an impermeable mass of salt in a *salt dome trap* (Figure 13.9d).

Extracting oil and gas by drilling deep into Earth's crust has become a very sophisticated and expensive business. Offshore platforms can drill into hydrocarbon reservoirs deep beneath the seafloor (Figure 13.10), which has opened vast areas of the continental margins to oil and gas production. Seismic imaging can map the reservoir rocks in three dimensions (see Figure 11.6), showing where the bulk of the oil and gas is located and mapping how it will flow from holes drilled into the reservoir. Water and carbon dioxide can be pumped down strategically positioned drill holes to push the oil into areas where it can be more efficiently recovered through other drill holes. These methods have increased the amount of oil and gas that can be extracted from hydrocarbon reservoirs and have thus increased our fossil-fuel reserves.

In their search for petroleum, geologists have seismically mapped thousands of oil traps throughout the world. Only a fraction of them have proven to contain economically valuable amounts of oil or gas, because traps alone are not enough to create a hydrocarbon reservoir. A trap will contain oil only if source beds were present, the necessary chemical reactions took place, and the oil migrated into the trap and stayed there without being disturbed by subsequent heating or deformation. Most of the large hydrocarbon reservoirs have already been discovered, and finding major new reservoirs is becoming more difficult.

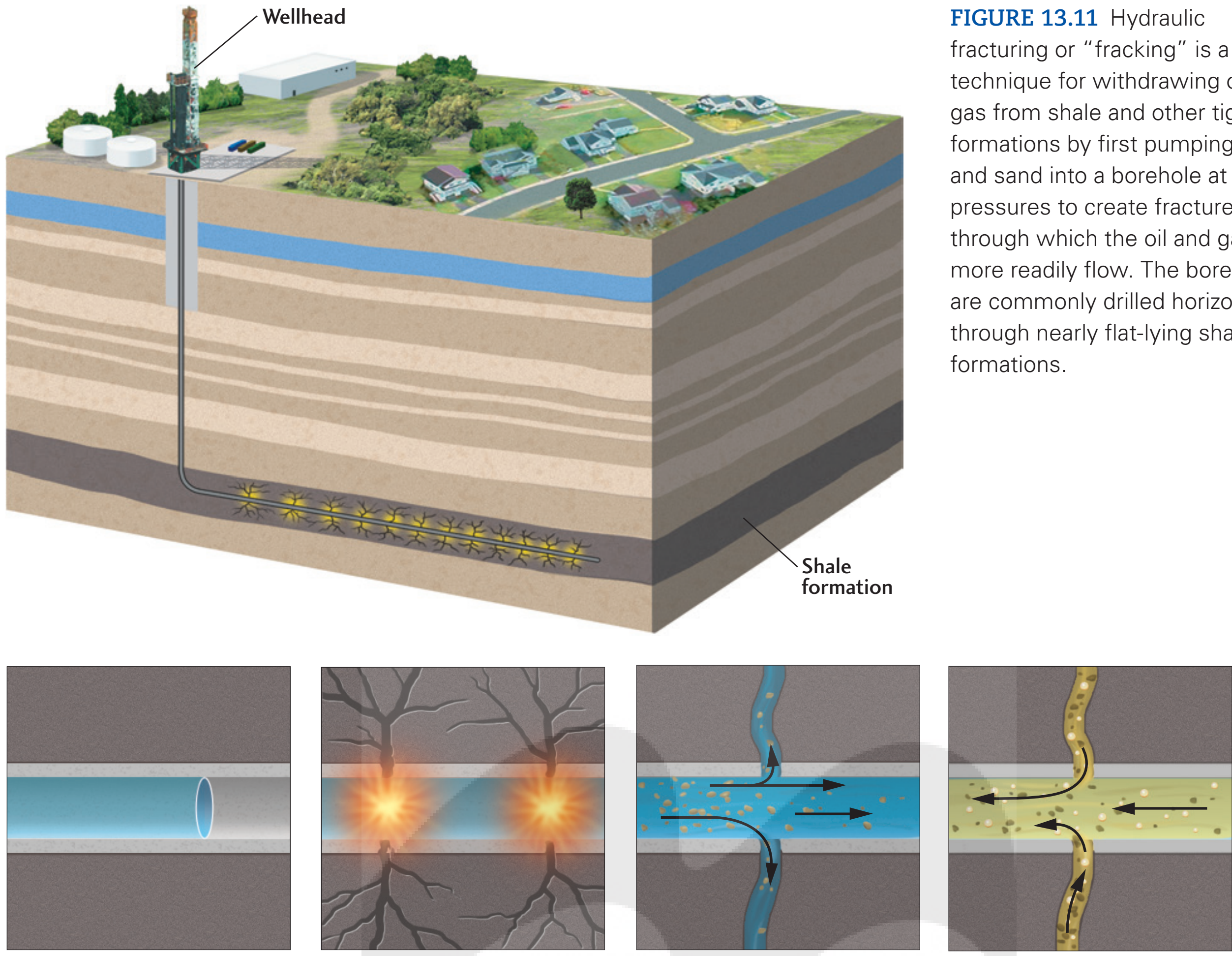
Producing Oil and Gas from Tight Formations

Hydrocarbons are very common in sedimentary rocks, but only a small fraction has been concentrated as oil and gas in easily drilled reservoirs. The bulk of our petroleum resources are widely distributed, sealed within impermeable source beds called **tight formations.** Examples include extensive gas-rich shale deposits throughout North America, such as the Marcellus Formation that underlies the northern Appalachian Mountains and the Allegheny Plateau of the eastern United States (see Figure 6.21). Petroleum engineers have developed more efficient ways to extract oil and natural gas from tight formations. They use three-dimensional models of the sedimentary structures and sophisticated navigation systems to steer drill bits on horizontal paths through flat-lying sedimentary rocks, and they inject large amounts of water and sand through holes in the drill pipe to create tiny fissures in the rock, which allows gas to flow more readily back into the pipe (Figure 13.11). This combination of **horizontal drilling** and **hydraulic fracturing** (or "**fracking**") has revolutionized the oil and gas industry. The proven reserves of gas from shales and other tight formations now exceeds conventional gas reserves.

Distribution of Oil Reserves

In the decade 2007–2017, the world consumed about 0.33 trillion barrels of oil (1 barrel = 42 gallons). Yet, the worldwide reserves of oil did not decline; they *increased* by about the same amount, from about 1.43 trillion barrels in 2007 to 1.70 trillion barrels in 2017. Oil exploration is an immensely successful geologic activity!

Oil reserves and their decadal changes are displayed by region in Figure 13.12. The oil fields of the Middle East—including Iran, Kuwait, Saudi Arabia, Iraq, and the Baku region of Azerbaijan—account for 48 percent of the world's total. Here, sediments rich in organic material have been folded and faulted by the closure of the ancient Tethys Ocean, forming a nearly ideal environment for oil accumulation. The extensive reservoirs discovered in this vast convergence zone include the world's largest, the Ghawar



(a) Borehole is cased and surrounded by cement.

(b) Small holes are blasted through casing and cement.

(c) Surrounding rocks are hydraulically fractured by pumping water and sand into borehole at high pressure.

(d) Fracking generates small fissures that are kept open by the sand, allowing oil and gas to flow up the borehole to the wellhead.

FIGURE 13.11 Hydraulic fracturing or "fracking" is a technique for withdrawing oil and gas from shale and other tight formations by first pumping water and sand into a borehole at high pressures to create fractures through which the oil and gas can more readily flow. The boreholes are commonly drilled horizontally through nearly flat-lying shale formations.

field in Saudi Arabia. Ghawar has produced about 70 billion barrels of oil since its opening in 1948 and may produce another 70 billion barrels over its remaining lifetime.

Most of the oil reserves in the Western Hemisphere are located in the highly productive Gulf Coast–Caribbean area, which includes the Louisiana–Texas region, Mexico,

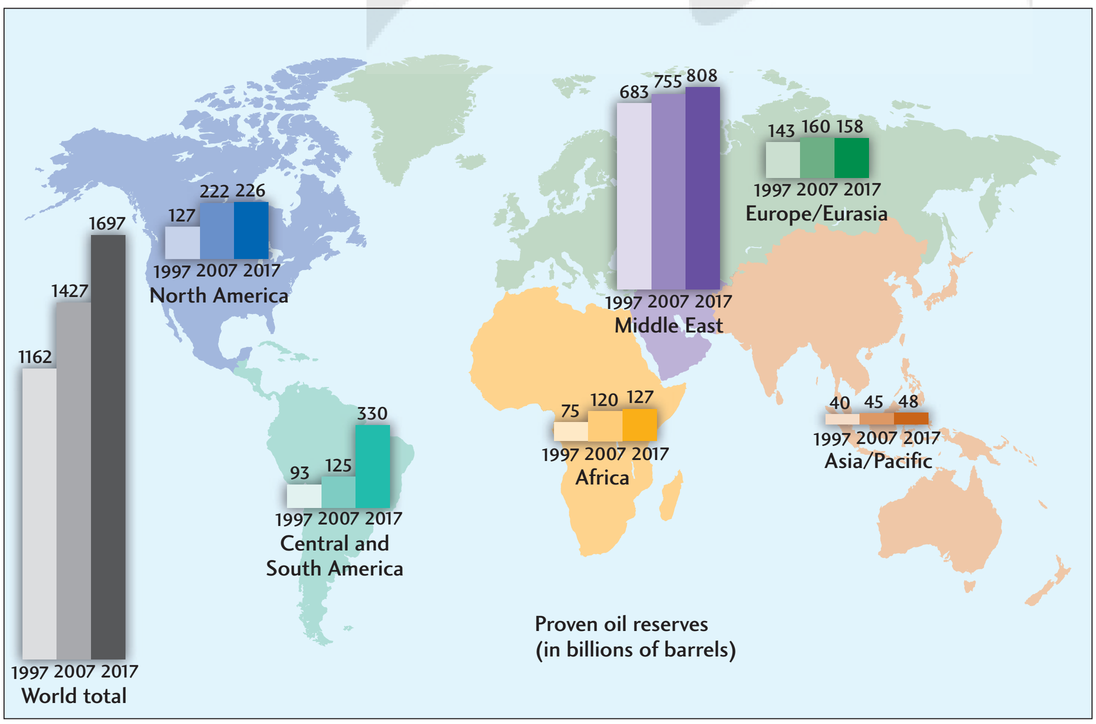


FIGURE 13.12 Regional estimates of world oil reserves in 1997 (left bar), 2007 (middle bar), and 2017 (right bar) in billions of barrels (bbl). The total world oil reserves in 2017 were 1.7 trillion barrels. [Data from the *British Petroleum Statistical Review of World Energy 2017*.]

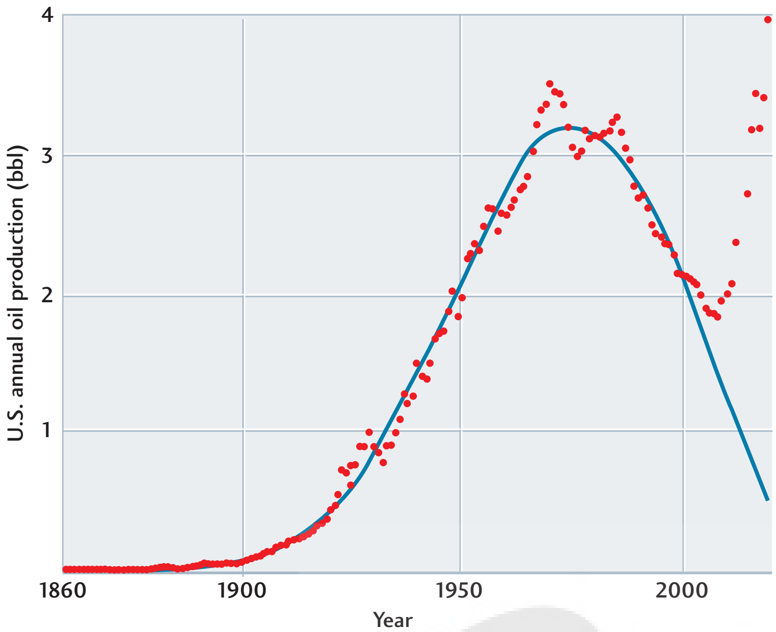


FIGURE 13.13 U.S. annual crude oil production in billions of barrels from 1860 to 2018. The red points show production figures for each year. The solid blue line is similar to Hubbert's 1956 projection, which predicted the peak in the 1970s and the subsequent decline. However, production reached a minimum in 2008 and has since been rapidly increasing, reaching nearly 4 billion barrels in 2018. [Data from the U.S. Energy Information Administration and from K. Deffeyes, *Hubbert's Peak*. Princeton, NJ: Princeton University Press, 2001.]

Colombia, and Venezuela. The threefold increase in South American oil reserves from 2007 to 2017 came mainly from improvements in oil-recovery technology, which will allow the heavy oil of Venezuela's Orinoco Basin to be exploited economically, as well as the discovery of huge new oil fields in the Atlantic Ocean off Brazil.

The United States' oil reserves also increased, from 30 billion barrels in 2007 to 50 billion barrels in 2017, placing it ninth worldwide. Thirty-one U.S. states have commercial oil reserves, and small, noncommercial resources can be found in most of the others.

Oil Production

Global oil production in 2018 was about 30 billion barrels per year worldwide. The United States produced 4 billion barrels, more than any other nation. The United States is a mature oil producer, whose history of production provides insights into the future of the global fossil-fuel supply. Production reached a maximum in 1970 and declined, approximately following a bell-shaped curve (Figure 13.13).

The high point is referred to as **Hubbert's peak,** named for petroleum geologist M. King Hubbert. In the mid-1950s, Hubbert used a simple mathematical relationship between the production rate and the rate at which new reserves were being discovered to predict that U.S. oil production would begin to decline sometime in the early 1970s. His arguments were roundly dismissed as overly pessimistic because, at the time, oil production was still growing rapidly. But history proved him right. Production did indeed peak in 1970, beginning a decline that continued much as Hubbert predicted throughout the late twentieth century.

In 2009, however, U.S. oil production suddenly began to increase again, and that trend has accelerated: 2018 production was almost 4 billion barrels, more than twice the 2008 minimum and surpassing the 1970 value of 3.5 billion barrels. This increase signals a new U.S. oil boom, fed by the rapid development of offshore oil fields and improved technology for recovering oil on land, including the controversial technique of fracking. These same technologies, which are now being applied in other regions, have created an oil glut that has caused the price of oil to drop from over $100 per barrel in 2008 to about $50 in 2017. We are not about to run out of oil anytime soon! (See Earth Issues 13.1.)

Natural Gas

The world's reserves of natural gas are comparable to its crude oil reserves (see Figure 13.7) and will likely exceed them in the decades ahead. Estimates of natural gas resources have been rising in recent years because exploration for natural gas has increased, and gas reservoirs have been identified in new settings, such as very deep rock formations, overthrust structures, coal beds, tight formations of sandstones and shales. Fracking technology has created a boom in the extraction of natural gas from shale formations that are extensive throughout (see Chapter 6). The production of "tight gas" from shale and other tight formations has increased more than a factor of three since 2000 and now accounts for about two-thirds of U.S. natural gas production (Figure 13.14).

Natural gas is a premium fuel for a number of reasons. In combustion, methane combines with atmospheric oxygen, releasing energy in the form of heat and producing only carbon dioxide and water. Natural gas therefore burns much more cleanly than oil or coal, which also produces sulfur dioxide (the major cause of acid rain). Moreover, natural gas emits 30 percent less CO_2 per unit of energy than oil and more than 60 percent less than coal. Therefore,

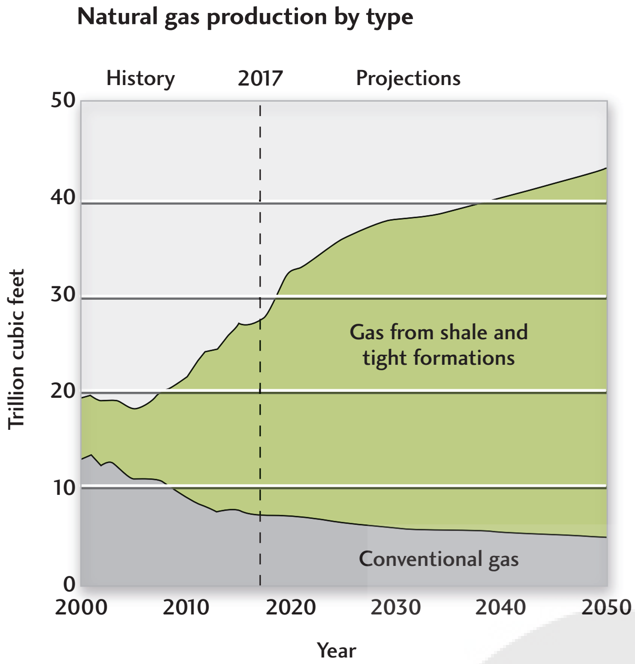


FIGURE 13.14 Gas produced from shales and other tight formations now accounts for almost two-thirds of natural gas production in the United States, and it is expected to constitute almost three-fourths by 2040. [Data from the U.S. Energy Information Administration, 2017.]

substituting natural gas for coal as, say, the fuel for power plants, lowers the carbon intensity of energy production (see the Practicing Geology Exercise at the end of this section). Natural gas is easily transported across continents through pipelines. Getting it from source to market across oceans has been more difficult. The construction of tankers and ports that can handle liquefied natural gas (LNG) is beginning to solve this problem, although the potential dangers (such as the risk of a large explosion) have made LNG facilities controversial in the communities where they would be located.

Natural gas accounts for an increasing percentage of all fossil-fuel consumption in the United States, about 35 percent in 2017 (see Figure 13.5). More than half of U.S. homes and a great majority of commercial and industrial buildings are connected to a network of underground pipelines that draw gas from fields in the United States, Canada, and Mexico. The rise of natural gas consumption relative to petroleum (see Figure 13.2) has led some observers to predict that we are now transitioning from a "petroleum economy" to a "methane economy."

Coal

There are huge resources of coal in sedimentary rocks. Although coal has been a major energy source since the late nineteenth century, only about a few percent of the world's coal reserves have been consumed. According to the best estimates, these reserves amount to 860 billion metric tons, which are capable of producing 17,800 quads of energy, more than any other fossil fuel (see Figure 13.7). About 85 percent of the world's coal resources are concentrated in the Russian Federation, China, and the United States; these countries are also the world's largest coal producers. The United States has the largest reserves (**Figure 13.15**)—enough to last for a few hundred years at the nation's

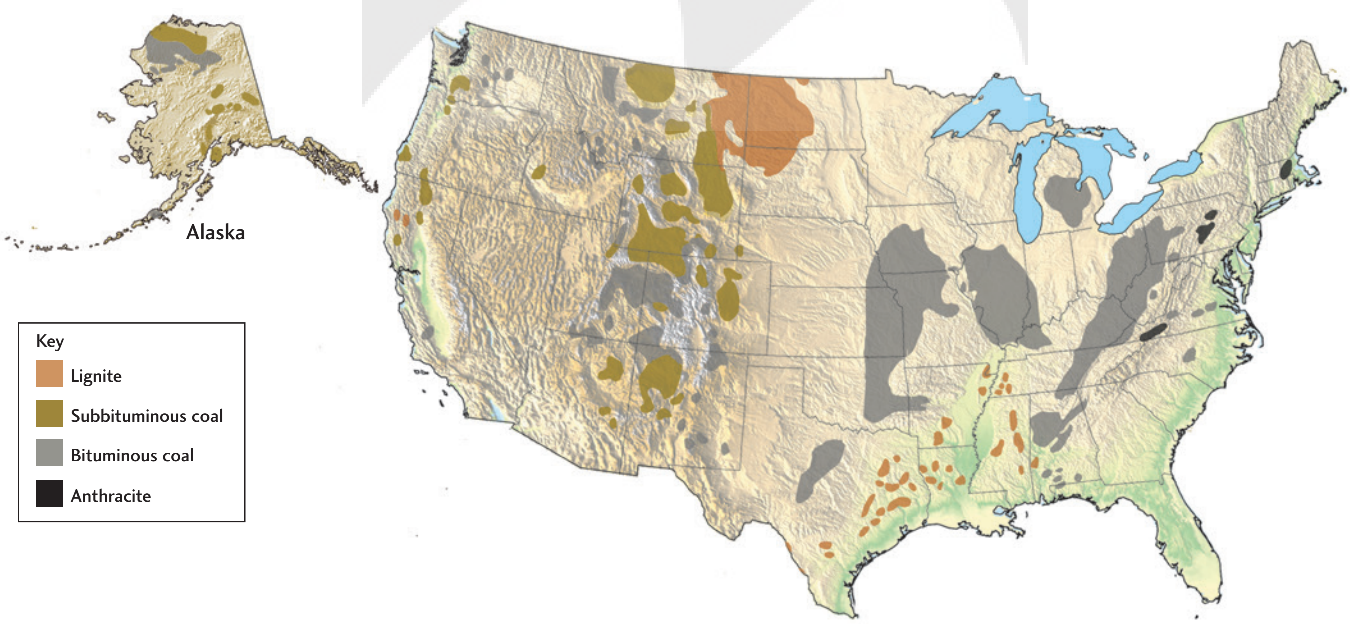


FIGURE 13.15 Coal resources of the United States. In 2017, U.S. coal reserves were 251 billion metric tons, about one-quarter of the global total. [U.S. Bureau of Mines.]

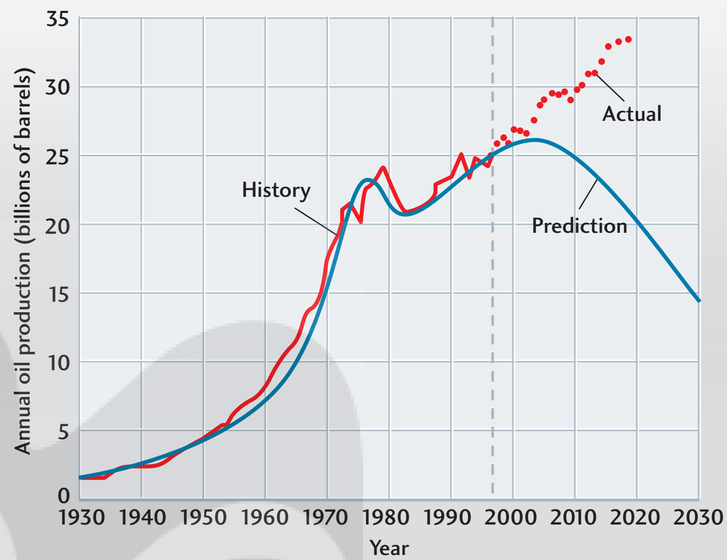
Earth Issues 13.1 When Will We Run Out of Oil?

At the current production rate, the world would consume all of today's oil reserves in about 55 years. Does that mean we will run out of oil before the end of this century? No, because oil resources are much greater than oil reserves.

In fact, we will never really "run out" of oil. As resources diminish, prices will eventually rise so high that we cannot afford to waste oil by burning it as a fuel. Its main use will then be as a raw material for producing plastics, fertilizers, and a host of other petrochemical products. The petrochemical industry is already a very big business, consuming 7 percent of global oil production. As oil geologist Ken Deffeyes has noted, future generations will probably look back on the Petroleum Age with a certain amount of disbelief: "They burned it? All those lovely organic molecules, and they just burned it?"

The key question is not when oil will run out, but when oil production will stop rising and begin to decline. This milestone—Hubbert's peak for world oil production—would be the real tipping point; once it is reached, the gap between supply and demand would grow rapidly, driving oil prices sky-high.

So how close are we to Hubbert's peak? The answer to this question has been the subject of considerable debate. Hubbert himself predicted that world oil production would peak around the year 2000. Production using conventional recovery techniques on land did indeed reach a maximum about that time (2003) and have since declined. But Hubbert and other "oil pessimists" did not account for new technologies such as fracking and offshore drilling, which have substantially increased global oil reserves (see Figure 13.12) and spurred the remarkable resurgence of U.S. oil production (see Figure 13.13). Reaching Hubbert's peak now appears to be much less of an economic danger than the costly environmental effects of burning fossil fuels, especially the tremendous potential costs of polluting the atmosphere with carbon dioxide and other greenhouse gases.



Based on data up to 1996 (red line), the oil geologist Colin Campbell published a prediction (blue line) that Hubbert's peak in global oil production would occur in the early 2000s. Actual production (red dots) has instead grown rapidly, owing almost entirely to increases from unconventional oil resources such as fracking and offshore drilling. [Prediction from C. J. Campbell & J. H. Laherrère, *Scientific American*, March 1998; data from *British Petroleum Statistical Review of World Energy 2018*.]

current rate of use (about 800 million tons per year). From 1975, when the price of oil began its precipitous rise, until 2005, coal supplied an increasing proportion of U.S. energy needs, primarily as fuel for electrical power generation. But coal usage has since declined precipitously as natural gas production has increased (see Figure 13.2). Coal currently accounts for about 14 percent of U.S. energy consumption.

Other Hydrocarbon Resources

Extensive deposits of hydrocarbons occur in two other forms: (1) source beds that are rich in organic material but never reached the oil window, and (2) formations that once contained oil but have since "dried out," losing many of their volatile components, to form a tarlike substance called *natural bitumen* (not to be confused with bituminous coal).

A hydrocarbon resource of the first type is *oil shale*, a fine-grained, clay-rich sedimentary rock containing large amounts of organic matter. In the 1970s, oil producers began trying to commercialize the extensive oil shales of western Colorado and eastern Utah, but those efforts were largely abandoned by the 1980s as petroleum prices fell, concerns over environmental damage increased, and technical problems persisted. The methods in use require the mining of oil shale, which is then crushed and heated to extract "shale oil" (not to be confused with "tight oil" derived by the fracking of shale beds and other tight formations). This process is expensive, consuming so much energy and producing so much environmentally dangerous waste material that the commercial production of shale oil is not currently feasible. However, new techniques, such as the production of shale oil by heating the rock formations in place, could change the economics. The resource implications would be significant, because the total amount of petroleum potential

PRACTICING GEOLOGY EXERCISE

Carbon Intensity of Fossil-Fuel Burning

The carbon intensity of a fuel is defined to be the mass of carbon emitted as CO_2 per unit of useful energy produced by burning the fuel. The amount of carbon emitted for a particular fossil-fuel type is a fixed fraction of its mass. For example, the burning of methane is represented by the following chemical equation:

$$CH_4 + 2O_2 = CO_2 + 2H_2O + \text{heat energy}$$

The amount of carbon (atomic mass of 12) emitted by the burning of 1 gigaton (10^{12} kg) of methane (atomic mass of 16) is 1 Gt × 12/16 = 0.75 Gt of carbon. We can also measure the heat energy released during the reaction, which is 52 quads per gigaton of methane. The carbon intensity of methane burning is the ratio of these two quantities:

$$\text{carbon intensity} = \frac{\text{carbon emitted}}{\text{energy produced}} = \frac{0.75\ \text{Gt}}{52\ \text{quads}} = 0.014\ \text{Gt/quad}$$

The carbon intensities of other fossil fuels are 0.020 Gt/quad for crude oil and 0.025 for coal, summarized in the following graph:

recoverable from known oil shale deposits is about 3 trillion barrels, twice the reserves of conventional petroleum.

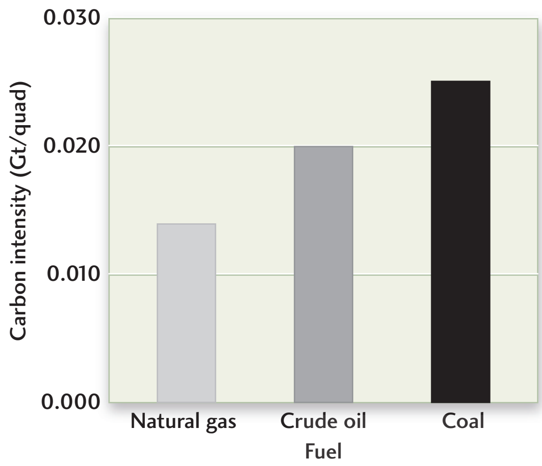
A deposit of the second type, the *tar sands* of Alberta, Canada, is estimated to contain a hydrocarbon reserve equivalent to 170 billion barrels of oil and a total resource perhaps 10 times that amount—comparable to the worldwide reserves of conventional petroleum (Figure 13.16). More than 900 million barrels of oil are now extracted from the Alberta tar sands each year, but further development of the tar sands, like oil shales, raises important environmental concerns. It takes 2 tons of mined sand and 3 barrels of water to produce 1 barrel of oil, leaving lots of waste sand and water, which are environmental pollutants. Moreover, production of oil from the tar sands is an inefficient process that sucks up about two-thirds of the energy they ultimately render, and its carbon intensity is significantly higher than conventional oil production.

Environmental Costs of Extracting Fossil Fuels

Although the pollution of the atmosphere with greenhouse gases is the most serious environmental problem associated with the use of fossil fuels, the process of extracting a fossil fuel from the lithosphere can itself have serious detrimental effects on the environment. We illustrate the problems with a few examples.

Coal The extraction and combustion of coal present serious problems that make it a less desirable fuel than oil or natural gas. Underground coal mining is a dangerous profession; more than 2000 miners are killed each year in China alone. Many more coal miners suffer from black lung, a debilitating inflammation of the lungs caused by the inhalation of coal particles. Surface or "strip"

FIGURE 13.16 Surface mining of the Athabasca tar sands in Alberta, Canada, now produces more than 900 million barrels of oil each year. [dan_prat/Getty Images.]



You can see that crude oil emits 40 percent more carbon per unit of energy than natural gas, and coal emits 70 percent more. Therefore, switching coal-fired electrical plants to gas-fired plants can substantially reduce the CO_2 emitted into the atmosphere.

Other measures of carbon intensity can be derived from these numbers. For example, according to Figure 13.5, the mix of fuels used to generate electrical power in the United States produces 38 quads of energy and emits 0.57 Gt of carbon for a combined carbon intensity of 0.015 Gt/quad. Note that this value is only slightly more than that of natural gas, the least carbon intensive of the fossil fuels, even though the U.S. energy system uses comparable amounts of crude oil and coal. Why? Because alternative sources of energy with very low carbon intensities—nuclear, hydroelectric, wind, and solar—also contribute substantially to energy production.

BONUS PROBLEM: Using the data in Figure 13.5 and assuming only the fossil fuels produce carbon dioxide, calculate the carbon intensity factor for the fossil-fuel component of the U.S. energy system.

mining—the removal of soil and surface sediments to expose coal beds—is safer for the miners, but it can ravage the countryside if the land is not restored. An especially destructive type of surface mining, now common in the Appalachian Mountains of the eastern United States, is "mountaintop removal," in which up to 300 vertical meters of a mountain crest is blasted away to expose underlying coal beds (**Figure 13.17**). The excess rock and soil are dumped into the surrounding valleys.

Coal is a notoriously dirty fuel. In addition to its high carbon intensity, most coal also contains appreciable amounts of pyrite, which is released into the atmosphere as noxious sulfur-containing gases when the coal is burned. Smog and acid rain, which forms when these gases combine with rainwater, has been a severe problem in many countries, especially China. U.S. government regulations now require industries that burn coal to adopt technologies for "clean" coal combustion, which have reduced emissions of sulfur and toxic chemicals. Federal laws also mandate the restoration of land disrupted by surface mining and the reduction of dangers to miners. These measures are expensive and add to the cost of coal, which is one reason why coal has declined substantially as a component of the U.S. energy mix (see Figure 13.2).

FIGURE 13.17 Mining of coal by mountaintop removal in the Appalachian Mountains of West Virginia. [Rob Perks, Natural Resources Defense Council.]

Oil On April 20, 2010, an explosion aboard the drilling platform *Deepwater Horizon* killed 11 men and injured 17 others. This blowout resulted in the largest marine oil spill in history, releasing 5 million barrels of crude oil into the Gulf of Mexico during the next 3 months (**Figure 13.18**). The oil spill caused significant environmental damage to ecosystems along the Gulf Coast.

This accident, like the infamous spills off the Yucatan coast in 1979 and Santa Barbara in 1969, renewed the long-running debate about whether to allow drilling for oil in fragile habitats such as the Arctic National Wildlife Refuge (ANWR) on the coastal plain of northern Alaska. The total petroleum resource in ANWR has not been fully evaluated, but it could be as much as 80 billion barrels of oil. The USGS estimates that if oil prices were high enough and environment restrictions relaxed, 6 billion to 16 billion barrels of this oil could be produced economically using current technologies. There is no doubt that these resources would contribute to the national economy. But oil and gas production would require the building of roads, pipelines, and housing in a delicate environment that is an important breeding area for caribou, musk-oxen, snow geese, and other wildlife (**Figure 13.19**). Policy makers must weigh the short-term economic benefits of drilling against possible long-term environmental losses in making this decision.

Natural Gas We have seen how the technologies of precisely guided horizontal drilling and hydraulic fracturing have contributed to a recent boom in U.S. natural gas production. The environmental costs associated with fracking can be steep, however, because the process uses huge amounts of water, and wastes from shale gas production can contaminate the local water supply. Moreover, the disposal

FIGURE 13.18 (a) Oil slick in the Gulf of Mexico imaged on May 24, 2010 by NASA's Terra satellite, 34 days after the explosion of the *Deepwater Horizon*. (b) The oil spilled by the *Deepwater Horizon* blowout harmed wildlife along the Gulf Coast. [a: Michon Scott/NASA Earth Observatory/Goddard Space Flight Center; b: AP Photo/Bill Haber.]

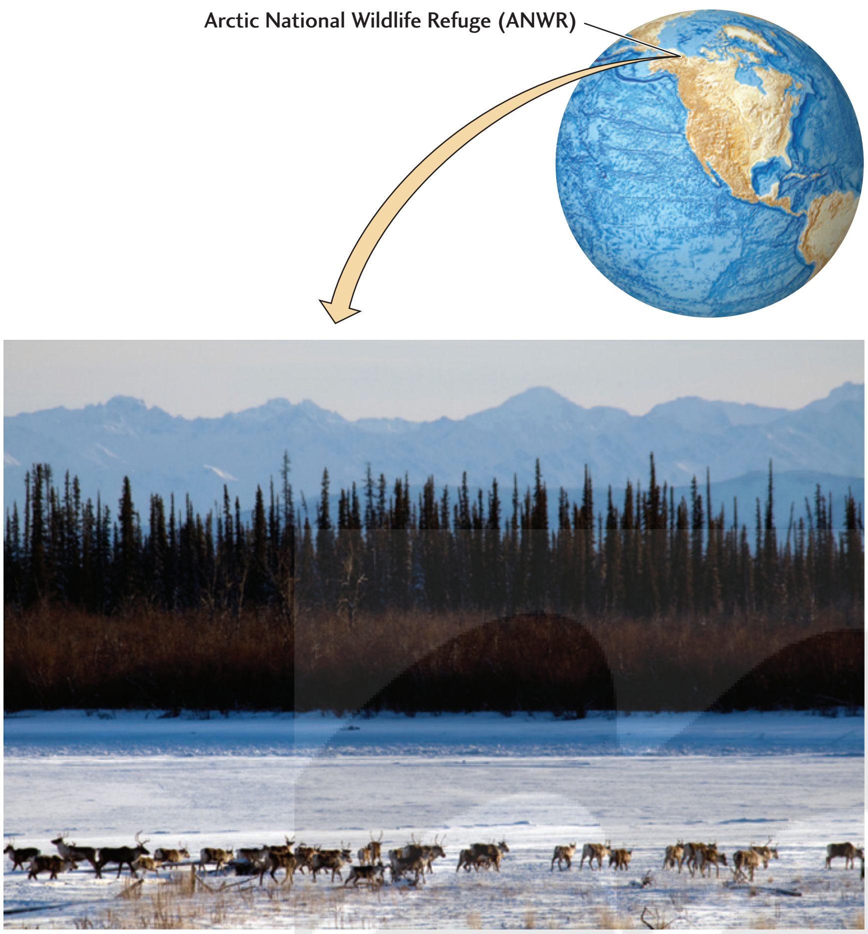


FIGURE 13.19 Herd of caribou in the Arctic National Wildlife Refuge (ANWR). An intense controversy surrounds proposals to drill for oil and natural gas in this pristine region. [Prisma by Dukas Presseagentur GmbH/Alamy.]

of waste water and chemicals used in fracking and other unconventional recovery methods is often done by injecting these fluids into deep wells, which lubricates old faults in Earth's crust, causing earthquakes. This practice has increased earthquake activity in many regions of the United States where the seismicity has been historically low, such as Oklahoma, Texas, and Ohio (see Earth Issues Box 10.2).

Alternative Energy Resources

Fossil fuels account for 81 percent of the world's primary energy production, about the same fraction as for the United States (Figure 13.20). The data from the previous section demonstrate that there are plenty of fossil-fuel resources to power civilization for decades, perhaps centuries, into the future. It is nevertheless clear that our society can ill afford to continue its dependence on fossil fuels, owing to the loading of the atmosphere with carbon dioxide. We will now explore the alternative sources of energy that have the greatest potential to replace fossil fuels, assessing the factors that are helping and hindering progress towards a "decarbonized" energy system.

Nuclear Energy

The first large-scale use of the radioactive isotope uranium-235 to produce energy was as an atomic bomb in 1944, but the nuclear physicists who first observed the

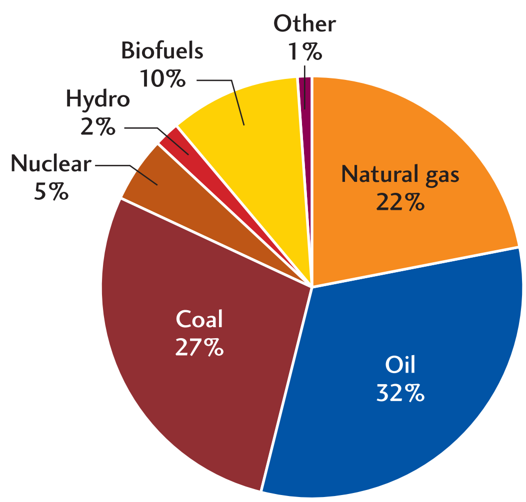


FIGURE 13.20 Distribution of world primary energy production by source. In 2017, the total energy production was 536 quads. [Data from the International Energy Agency, 2018.]

vast energy released when its nucleus split spontaneously (a phenomenon called *fission*) foresaw the possibility of peaceful applications of this new energy source. After World War II, countries around the world built nuclear reactors to produce **nuclear energy.** In these reactors, the fission of uranium-235 releases heat that is used to make steam, which then drives turbines to create electricity. A typical commercial reactor produces about 1000 megawatts of electricity (1 megawatt = 1 million watts). Large nuclear facilities may have multiple reactors (**Figure 13.21**).

Nuclear power supplies a substantial fraction of the electric energy used by some countries, such as France (72 percent in 2017), Slovakia (54 percent), and Sweden (40 percent), but this proportion is much smaller in the United States. Overall, the nation's 100 nuclear reactors produce 20 percent of U.S. electricity, accounting for about 8.6 percent of total U.S. energy demand (see Figure 13.5). Worldwide, this fraction is only 4.5 percent.

Uranium Reserves Uranium is an extremely rare element in the Earth, but the melting of mantle and crustal rocks tends to concentrate it in the upper crust, where it is 50 times more common than silver and 1800 times more common than gold. Minable concentrations are found as small quantities of uraninite, a uranium oxide mineral (UO_2, also called pitchblende), in veins in granites and other felsic igneous rocks. Uranium is highly soluble in groundwater and can be precipitated as uraninite in sedimentary rocks. High-grade uranium ores can contain several percent uranium. In its native form, only a small proportion (about 0.7 percent) is uranium-235. The much more abundant isotope, uranium-238, is not radioactive enough to be used as a nuclear fuel. The proven reserves of uranium, about 5.9 megatons worldwide, correspond to about 3200 quads of nuclear energy, enough to supply the existing nuclear power plants with fuel for 90 years.

Can Nuclear Energy Reduce Global Carbon Emissions? The total uranium resources are much larger than its reserves, of course, and many energy experts believe that the accelerated development of these resources could supply the world with enough nuclear energy to substantially reduce carbon emissions. Nuclear reactors release no greenhouse gases into the atmosphere—the carbon intensity of nuclear-fuel burning is essentially zero. It is not exactly zero if one takes into account the complete "energy life-cycle," because some fossil-fuel energy must be expended (e.g., in driving diesel-powered vehicles) to build, operate, and decommission nuclear plants and to the transport of nuclear energy from the plant to where it can be used. Taking these fossil-fuel expenditures into account, one finds that the carbon intensity of electricity generation by nuclear energy is only about 3 percent of that of natural gas, the cleanest fossil fuel.

As of January 2019, there were 450 nuclear power plants worldwide, accounting for 11 percent of global electricity generation, and another 60 or so are under construction, including two in the United States. A crash program to build hundreds more over the next few decades could reduce global carbon emissions by a billion tons per year—a prospect we will consider further in the next chapter. That is unlikely to happen, however, owing to societal anxieties about nuclear hazards.

FIGURE 13.21 Japan's Kashiwazaki-Kariwa facility is the world's largest nuclear power plant, with seven reactors and a total generating capacity exceeding 8200 megawatts. It was completely shut down after several reactors were damaged by a powerful earthquake (magnitude 6.6) that struck close by on July 16, 2007, and again after the great Tohuku earthquake (magnitude 9.0) badly damaged the Fukushima Daiichi nuclear plant on March 11, 2009. Two reactors are scheduled to restart in 2019. [STR/AFP/Getty Images.]

Hazards of Nuclear Energy The biggest drawbacks of nuclear energy are concerns regarding the safety of nuclear reactors, the risk of environmental contamination with radioactive material, and the potential use of radioactive fuels for making nuclear weapons.

In the United States, damage to a reactor at the Three Mile Island reactor in Pennsylvania in 1979 released radioactive debris. Although very little radioactive fuel left the containment building, and no one was harmed, it was a close call. Much more serious was the destruction of a nuclear reactor in the town of Chernobyl, Ukraine, in 1986. The reactor went out of control because of its poor design and human error. Thirty-one people were killed, and a plume of radioactive debris was carried by winds over Scandinavia and western Europe. Contamination of buildings and soil has made hundreds of square miles of land surrounding Chernobyl uninhabitable. Food supplies in many countries were contaminated by the radioactive fallout and had to be destroyed. Eventual deaths from cancer caused by exposure to the fallout may be in the thousands.

A second serious disaster occurred when the tsunami from the great Tohoku earthquake of March 11, 2011, inundated the Fukushima Daiichi nuclear power plant on the northeastern coast of Honshu, Japan (see Figure 10.31). The reactors shut down, as designed, but the tsunami destroyed the backup diesel generators, cutting power to the water pumps that were supposed to cool the still-hot reactors. Three of the six reactors suffered complete or partial meltdowns, and explosions of hydrogen gas generated during the meltdowns destroyed the reactor containment buildings, releasing radioactive debris into the atmosphere. Water sprayed to cool the damaged reactors carried radioactive material into the ocean. Radioactive materials from these reactors are still leaking into the environment.

The uranium consumed in nuclear reactors leaves behind dangerous radioactive wastes. A system of safe long-term waste disposal is not yet available, and reactor wastes are being held in temporary storage facilities at reactor sites. This is a dangerous practice; spent fuel rods stored on site contributed to the radioactive debris released at Fukushima. Many scientists believe that geologic containment—the burial of nuclear wastes in deep, stable, impermeable rock formations—would provide safe storage of the most dangerous wastes for the hundreds of thousands of years required before they decay. France and Sweden have built underground nuclear waste repositories. A national repository, the Yucca Mountain Nuclear Waste Repository, was being developed in the United States at its nuclear-weapon test site in Nevada (Figure 13.22), but local opposition caused the federal government to terminate funding for the site in 2011. At present the United States has no long-term plan for nuclear waste disposal.

FIGURE 13.22 Aerial view of the north entrance to the Yucca Mountain Nuclear Waste Repository developed at the Nevada Test Site, north of Las Vegas. Yucca Mountain is the high ridge to the right of the entrance. Federal funding for this project was terminated in 2011. [Department of Energy.]

Biofuels

Before the coal-fired Industrial Revolution of the mid-nineteenth century, the burning of wood and other biomass derived from plants and animals satisfied most of society's energy needs. Even today, the burning of biomass contributes more than 10 percent to the global energy mix, exceeding the total derived from all other renewable resources (see Figure 13.20). Biomass is an attractive alternative to fossil fuels because, at least in principle, it is *carbon-neutral*; that is, the CO_2 produced by the combustion of biomass is eventually removed from the atmosphere by plant photosynthesis and used to produce new biomass.

Liquid **biofuels** derived from biomass, such as *ethanol* (ethyl alcohol: C_2H_6O), could replace gasoline as our main automobile fuel. The use of biofuels in transportation is hardly new. The first four-stroke internal combustion engine, invented by Nikolaus Otto in 1876, ran on ethanol, and the original diesel engine, patented by Rudolf Diesel in 1898, ran on vegetable oil. Henry Ford's Model T car, first produced in 1903, was designed to operate on ethanol. But soon thereafter, petroleum from the new reserves discovered in Pennsylvania and Texas became widely available, and cars and trucks were converted almost entirely to petroleum-based gasoline and diesel fuel.

Ethanol can be mixed with gasoline to run most car engines built today. It is produced mainly from corn in the United States and from sugarcane in Brazil. For the last 35 years, the Brazilian government has been pushing to replace imported oil with domestic ethanol; in 2017, about 90 percent of Brazil's automobile fuels were running on "flex-fuel," a combination of gasoline and ethanol, which is typically 70 percent cheaper than gasoline. Brazil and the United States account for 85 percent of the global biofuel production.

A promising biomass crop is switchgrass, a perennial plant native to the Great Plains (Figure 13.23). Switchgrass has the potential to produce up to 1000 gallons of ethanol per acre per year, compared with 665 gallons for sugarcane and 400 gallons for corn, and it can be cultivated

FIGURE 13.23 Switchgrass, a perennial plant native to the Great Plains, is an efficient source of ethanol, the most popular biofuel. Here, geneticist Michael Casler harvests switchgrass seed as part of a breeding program to increase the plant's ethanol yield. [Wolfgang Hoffmann/USDA.]

on grasslands of marginal utility for other types of agriculture. Nevertheless, biofuel production competes with food production, so increasing the former drives up the price of the latter, which reduces the economic benefits of biofuels.

How environmentally beneficial are biofuels? Are they really carbon-neutral? As we saw for nuclear power, the carbon intensity of biofuels is not zero if you consider the complete energy life cycle, because the energy used to fertilize plants, transform them into biofuels, and deliver the biofuels to market comes primarily from fossil fuels. Moreover, the basic assumption of carbon neutrality—that all of the carbon emitted into the atmosphere from biofuel burning will eventually be returned to the biosphere—is not true. About one-quarter of the carbon dioxide emitted into the atmosphere by fuel burning of any type is absorbed into the oceans, causing detrimental ocean acidification (see the Practicing Geology Exercise in Chapter 12). The widespread use of biofuels for transportation would no doubt reduce the pumping of carbon from the lithosphere to the atmosphere, but experts are still arguing about the magnitude of that reduction.

Hydroelectric Energy

About 2.4 percent of global energy production is **hydroelectric energy**, derived from water moving under the force of gravity to drive turbines that generate electricity. Artificial reservoirs behind dams usually provide the water. Hydroelectric energy is a renewable energy source that ultimately comes from the Sun, whose energy drives the climate system and creates rainfall. It is also relatively clean, risk-free, and cheap to produce.

The Three Gorges Dam on the Yangtze River in China (Figure 13.24) is the world's largest hydroelectric facility. It is capable of generating 22,500 megawatts—nearly 5 percent of China's total electricity demand. The project was controversial, however, because the damming of the Yangtze caused flooding that has displaced over a million people.

In the United States, hydroelectric dams deliver about 2.7 quads annually, a small but locally important share of the nation's annual energy consumption. The state of Washington is the largest U.S. producer, obtaining almost 90 percent of its electricity from hydroelectric power.

The U.S. Department of Energy has identified more than 5000 sites where new hydroelectric dams could be built and operated economically. Such expansion would be resisted, however, because the dams would drown farmlands and wilderness areas under artificial reservoirs while adding only a small amount of energy to the U.S. supply. For this reason, most energy experts expect that the proportion of the nation's energy produced by hydroelectric power will actually decline in the future.

Wind Energy

Wind energy is produced by windmills that drive electric generators. Today, the generation of electricity by high-efficiency wind turbines is a fast-growing source of renewable energy; global production is currently increasing by 17 percent per year. Wind farms containing hundreds of turbines can produce as much electric power as a mid-sized nuclear power plant (Figure 13.25). Denmark is a leading wind-power nation in the world, now producing over 40 percent of its electric power by wind. In the United States, electricity from wind sources tripled between 2008 and 2018, and it currently accounts for just over 6 percent of all U.S. electrical power production.

The U.S. Department of Energy estimates that winds sufficient for power generation blow across 6 percent of the land area of the continental United States, and that those winds have the potential to supply more than one and a half times the nation's current electricity demand. But harvesting

FIGURE 13.24 The Three Gorges Dam on China's Yangtze River is about 2335 m (7660 feet) long and 185 m (616 feet) high. Its 32 generators are capable of producing 22,500 megawatts of hydroelectric power. [AP photo/Xinhua Photo, Xia Lin.]

this energy would require placing millions of windmills, each 100 m tall, across hundreds of thousands of square kilometers of land. Changes to the landscape required for industrial wind farming, as well as the low-frequency noise generated by the turbines, have made the siting of new facilities a controversial environmental issue in some regions.

Solar Energy

Solar-energy enthusiasts are quick to remind you that "every hour Earth receives from sunlight more energy than civilization uses in one year." **Solar energy** is the prime example of a resource that cannot be depleted by usage: The Sun will continue to shine for at least the next several billion years. Although using solar energy to heat water for homes, industries, and agriculture is economically profitable with existing technology, the methods for the large-scale conversion of solar energy into electricity are still inefficient and expensive. Nevertheless, the solar generation of electricity is increasing rapidly as large power plants are being built in response to voter mandates and government subsidies. The Ivanpah solar electric–generating system in California's Mojave Desert, commissioned in 2013, is the world's largest, capable of producing up to 392 megawatts of electricity (Figure 13.26).

Solar energy is only a miniscule fraction of global energy production (0.2 percent), but its growth rate of 23 percent per year is higher than any other energy source. In Great Britain—not known for its sunny skies—solar generation of electricity exceeded that from coal-fired power plants for the first time in 2016. In the United States, solar-energy production rose from 0.2 quad in 2012 to almost 0.8 quad in 2017, a fourfold increase in 5 years. Optimistic projections are that, worldwide, solar conversion could increase to as

FIGURE 13.25 Photo taken on Feb. 20, 2012, shows the scene of windmills at Jinshan wind power plant in northwest China's Gansu Province. The installed capacity of grid-connected wind power in China has reached 53 million kilowatts so far. China has replaced America to be the number one wind power country in the world. [Ma Xiaowei/Xinhua News Agency/eyevine/Redux.]

FIGURE 13.26 The Ivanpah solar electric generating system in California's Mojave Desert, commissioned in 2013, is the world's largest. More than 170,000 mirrors focus sunlight on three towers filled with water, producing steam that spins turbines that can generate up to 392 megawatts of electricity. [Gilles Mingasson/Getty Images for Bechtel.]

much as 12 quads per year in a decade or so, which would amount to about 2 percent of total energy production.

Geothermal Energy

Earth's internal heat can be tapped as a source of *geothermal energy*, as we described in Chapter 12. According to one Icelandic estimate, as much as 40 quads of electricity could be generated each year from accessible geothermal energy sources, but so far only a tiny fraction of that amount, about 0.3 quad per year, is actually being generated. Another 0.3 quad of geothermal energy is used for direct heating. At least 46 countries now use some form of geothermal energy.

Geothermal energy is unlikely to replace petroleum as a major source of power, though it may help to meet the energy needs of a postcarbon economy. Like most of the other energy sources, geothermal power usage can cause environmental problems. Regional ground subsidence can occur if hot groundwater is withdrawn without being replaced. Hydrothermal waters can contain salts and toxic materials dissolved from the hot rock. As in the case of fracking, the disposal of these wastewaters by reinjection into the crust can trigger earthquakes.

Our Energy Future

As the human population continues to grow and standards of living improve, civilization's need for more energy will continue to rise. According to estimates by the U.S. Energy Information Administration, 70 percent of the increase over the next several decades will come from developing countries. The consumption of fossil fuels will continue to grow, though it will be outpaced by the expansion of alternative energy sources (Figure 13.27).

- The fossil-fuel fraction of the world energy supply will decline only slightly, from 81 percent in 2017 to 78 percent in 2040.
- Petroleum will remain the largest source of energy, its share decreasing from 33 percent in 2017 to 30 percent in 2040.
- Among the fossil fuels, coal consumption will grow the slowest, and natural gas the fastest.
- Nuclear energy use will increase more rapidly than fossil-fuel use.
- Renewable energy will continue to be the world's fastest-growing source of energy, at an average rate of 2.6 percent per year.

These projections are uncertain owing to unanticipated events (such as global military conflicts) and technological advances (new methods for generating energy), but they indicate that civilization will continue to pump carbon from the lithosphere into the atmosphere at very high rates. The potential effects on the climate system and the biosphere are the subjects of the next chapter.

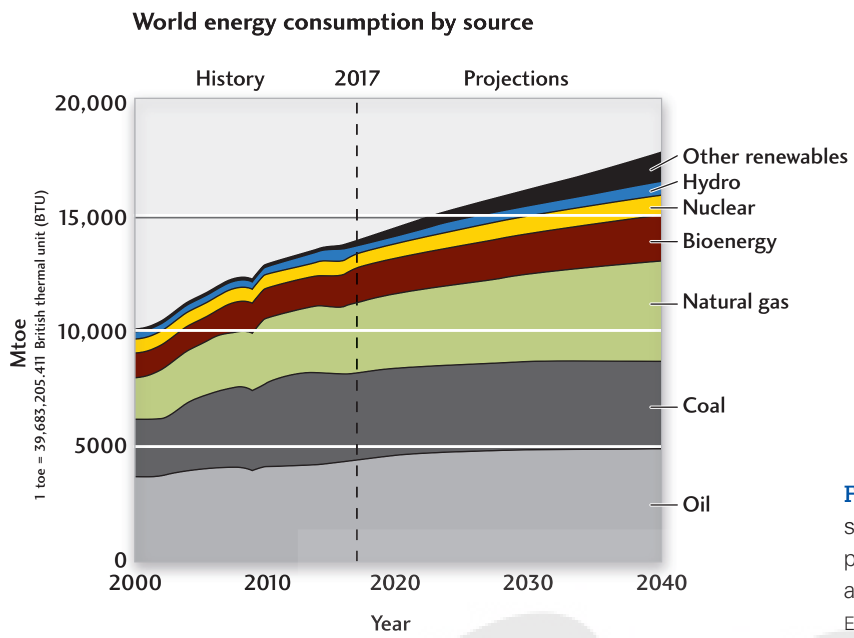


FIGURE 13.27 World energy consumption by source, 2000–2040. Values beyond 2017 are projections based on estimates of population and economic growth. [Data from the International Energy Agency, 2018.]

KEY TERMS AND CONCEPTS

biofuel (p. 383)
carbon intensity (p. 369)
coal (p. 371)
crude oil (p. 372)
energy resources (p. 367)
fossil fuels (p. 368)
horizontal drilling (p. 373)
Hubbert's peak (p. 375)
hydraulic fracturing (fracking) (p. 373)
hydrocarbon (p. 367)
hydrocarbon economy (p. 369)
hydroelectric energy (p. 384)
natural gas (p. 372)
nonrenewable resources (p. 368)
nuclear energy (p. 382)
oil trap (p. 372)
oil window (p. 372)
quad (p. 369)
renewable resource (p. 367)
reserves (p. 368)
solar energy (p. 385)
tight formation (p. 373)
wind energy (p. 384)

REVIEW OF LEARNING OBJECTIVES

13.1 Explain how the impact of civilization on the Earth system qualifies it as a global geosystem.

Human society has harnessed the means of energy production on a global scale and now competes with the plate-tectonic and climate systems in modifying Earth's surface environment. Most of the energy used by civilization today comes from hydrocarbon fuels. The rise of this hydrocarbon economy has altered the natural carbon cycle by creating a huge new flux of carbon from the lithosphere to the atmosphere. If that flow continues unabated, CO_2 concentrations in the atmosphere will double by the mid-twenty-first century.

Study Assignment: Review the section *Growth and Impact of Civilization.*

Exercise: List three facts that illustrate how civilization competes with plate tectonics and the climate system.

Thought Questions: (a) How is civilization fundamentally different from the natural geosystems we have studied in this textbook? (b) What factors do you think will be most important in influencing human population growth during this century?

13.2 Categorize our natural resources as renewable and nonrenewable, and differentiate energy reserves from energy resources.

Natural resources can be classified as renewable or nonrenewable, depending on whether they are replenished by geological and biological processes at rates comparable to the rates at which we are consuming them. Reserves are the known supplies of natural resources that can be exploited economically under current conditions.

Study Assignment: Figure 13.3

Exercises: (a) Figure 13.12 shows that petroleum reserves of South and Central America increased almost threefold during the decade 2007–2017. What factors contributed to this huge increase? (b) Which nonrenewable energy resource currently contributes most to the U.S. energy production? Which renewable energy resource?

Thought Question: How much larger are our fossil-fuel resources than our fossil-fuel reserves?

13.3 Understand the geological processes that form fossil fuels, and the energy available from their reserves.

Coal is formed by the burial, compression, and diagenesis of wetland vegetation. More compression and heating of coal beds generally increase the energy content of the coal. Oil and natural gas form from organic matter deposited in oxygen-poor sedimentary basins, typically on continental margins. These organic materials are buried as the sedimentary layers grow in thickness. Under elevated temperatures and pressures, the buried organic matter is transformed into liquid and gaseous hydrocarbons. Oil and gas accumulate where geologic structures, called oil traps, create impermeable barriers to their upward migration. Hydrocarbon resources also include oil shales that are rich in organic material but never reached the oil window and tar sands that once contained oil but have since lost most of their volatile components. The energy available from proven reserves of fossil fuels is estimated to be about 53,000 quads; at current rates of energy consumption, this is enough to fuel civilization for at least another century.

Study Assignments: Figures 13.9 and 13.10

Exercises: (a) What are the prerequisites for oil traps to contain oil? (b) An aggressive drilling program in the Arctic National Wildlife Refuge could produce as much as 16 billion barrels of oil. At current consumption rates, for how many years would this resource supply U.S. oil demand? (c) Which three countries have the largest coal reserves?

Thought Question: Which of the following factors are important in estimating the future supply of oil and natural gas: (i) the rate of oil and gas accumulation in traps, (ii) the rate of depletion of known reserves, (iii) the rate of discovery of new reserves, (iv) the total amount of oil and gas now present on Earth.

13.4 Answer the question: When will civilization run out of oil?

The short answer is not for a very long time. At the current production rate, the world would consume all of today's oil reserves in about 55 years; however, new technologies such as precise horizontal drilling and hydraulic fracturing are increasing oil reserves at a rapid rate, by over 20 percent in just the last decade. Moreover, oil can be derived from huge, unconventional hydrocarbon resources including oil shales and tar sands. Pessimistic predictions that global oil production would reach Hubbert's peak in the early twenty-first century—that it would stop rising and begin to decline—have not come true. In fact, we will never really run out of oil; as resources diminish and prices rise, oil will become primarily a raw material for producing plastics, fertilizers, and other petrochemical products.

Study Assignment: Earth Issues 13.1

Exercises: (a) Global oil production in 2018 was about 30 billion barrels per year worldwide. What is the equivalent energy expressed in quads? (b) Is petroleum consumption increasing or decreasing in the United States? Is it increasing or decreasing worldwide?

Thought Questions: (a) Are you an "oil optimist" or an "oil pessimist"? Explain why. (b) Why do some experts believe our energy economy is transitioning from a "petroleum economy" to a "methane economy"?

13.5 Compute the carbon intensities of fossil fuels from the energy they produce and the carbon dioxide they emit, and use carbon intensities to compute the changes in carbon flux from changes in energy production.

The carbon intensity of a fuel is defined to be the mass of carbon emitted as CO_2 per unit of useful energy produced by burning the fuel. The carbon emitted by burning 1 gigaton (Gt) of methane is 0.75 Gt, and the energy produced is 52 quads; the ratio of these two quantities, 0.014 Gt/quad, is the carbon intensity of methane burning. The carbon intensity of oil burning is 40 percent higher than this value, and that of coal burning is 70 percent higher, showing that natural gas is the least carbon-intensive fossil fuel and coal is the most. The overall carbon intensity of the U.S. electrical system is 0.015 Gt/quad, which is only slightly higher than that of natural gas, because the higher carbon intensity of coal is offset by the near-zero carbon intensity of nuclear and renewable energy sources. Replacing coal-fired electrical plants with gas-fired electrical plants would reduce the carbon intensity of the U.S. electrical system to 0.012 Gt/quad [see Exercise (b)].

Study Assignment: Practicing Geology Exercise

Exercises: (a) Which fossil fuel produces the least amount of CO_2 per unit of energy: oil, natural gas, or coal? Which produces the most? (b) About one-third of U.S. electrical-energy generation comes from burning coal. Show that the carbon intensity of this system would be reduced from 0.015 to 0.012 by replacing coal-fired plants with gas-fired plants.

Thought Question: Is the overall carbon intensity of the U.S. energy system increasing or decreasing? Why?

13.6 Quantify the relative contributions of alternative energy resources to energy production, and estimate their potential to satisfy future energy needs.

Alternative energy sources include nuclear power, biofuels, and solar, hydroelectric, wind, and geothermal energy. Taken together, these energy sources currently supply only a small percentage of world energy demand. Nuclear energy produced by the fission of uranium, the world's most abundant minable energy resource, could be a major energy source, but only if the public can be assured of its safety and security. Nuclear fuels have the potential of providing a large, low-cost source of energy that produces essentially no carbon dioxide. This promise has not been realized, however, owing to problems with reactor safety, disposal of radioactive wastes, and nuclear security. With advances in technology and reductions in cost, renewable sources such as solar energy, wind energy, and biomass could become major contributors in the twenty-first century.

Study Assignment: Review the section *Alternative Energy Resources*, especially Figure 13.20.

Exercises: (a) Contrast the risks and benefits of nuclear fission and coal combustion as energy sources. (b) Why is it untrue to assert that biofuels are carbon-neutral; that is, that all of the carbon emitted into the atmosphere from biofuel burning will eventually be returned to the biosphere?

Thought Questions: (a) What issues related to the use of nuclear energy can be addressed by geologists? (b) Given that solar energy is so plentiful, why is its contribution to the global energy supply so small?

13.7 Project the worldwide growth of energy consumption by geographic region and fuel type.

Population and economic growth increases energy consumption. As countries develop and living standards improve, energy demand grows rapidly. Based on growth projections, 72 percent of the increase in world energy consumption between now and 2040 will come from the developing countries, mostly in Asia, and only 18 percent from developed countries in North America, Europe, and Australia. Owing to this demand, energy production from all major sources will continue rise. The consumption of nuclear energy will climb. The most rapid growth will be in renewable energy sources. Energy from coal will level off, replaced primarily by increases in energy from natural gas. Consequently, the overall fraction of the world energy supply from fossil-fuel burning will decline only slightly, from 81 percent today to about 78 percent in 2040.

Study Assignment: Figures 13.6 and 13.27

Exercises: In 2017, global carbon emissions were 9.9 Gt from the global energy production of 536 quads. (a) What was the carbon intensity of the global energy system in 2017? (b) Based on Figure 13.27, is this carbon intensity in the future expected to increase, stay the same, or decrease? Why? (c) From the data in this chapter, calculate a rough estimate of the carbon intensity of the global energy system in 2040.

Thought Question: What do you think will be the major sources of the world's energy in the year 2040? In the year 2100?

VISUAL LITERACY EXERCISE

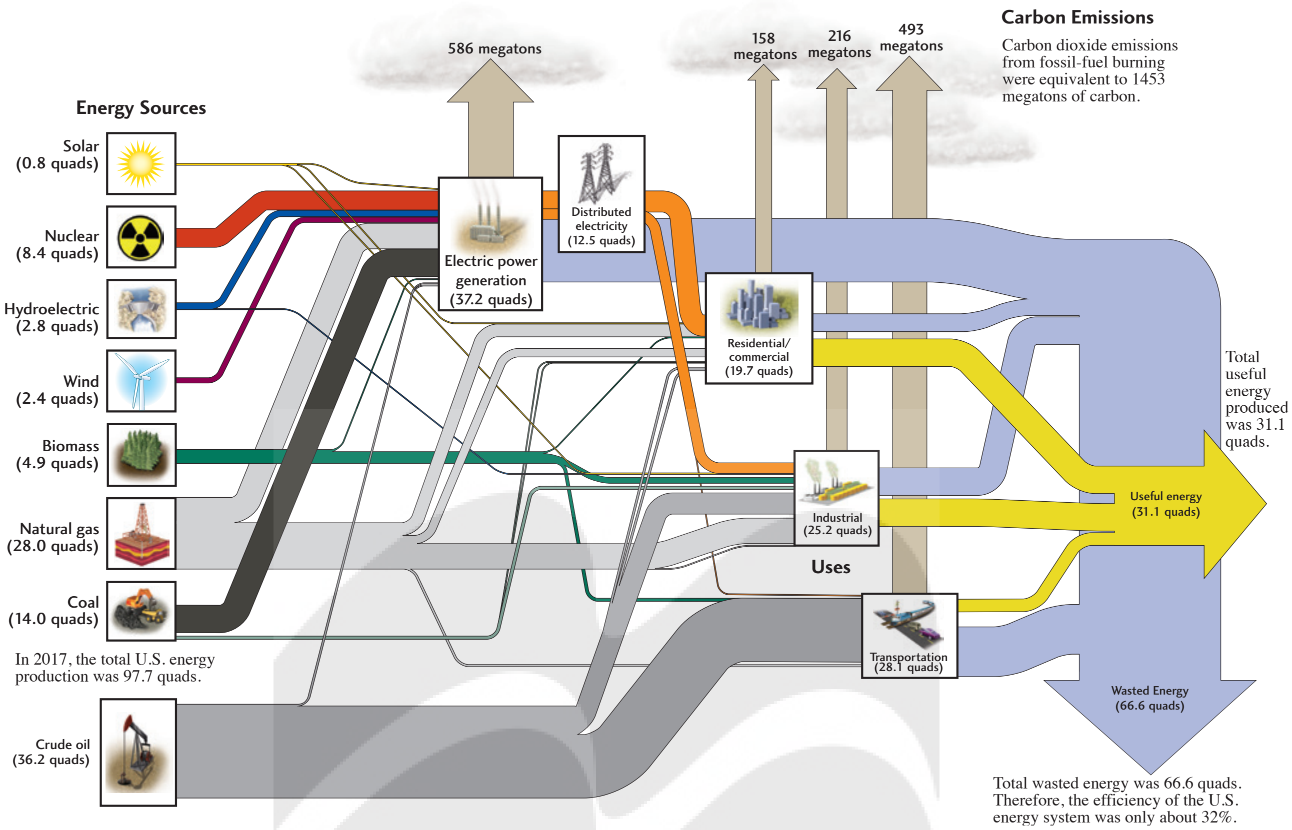


FIGURE 13.5 Energy consumption in the United States in 2017 (in quads). Energy from primary fuel sources (boxes on left side) is delivered to the residential, commercial, industrial, and transportation sectors (boxes in middle to right side). Not represented are small contributions to electric power generation from geothermal energy (0.2 quad). [Information from Lawrence Livermore National Laboratory, based on data from the Energy Information Administration.]

Figure 13.5 is a complicated diagram showing the energy consumption in the United States in 2017.

1. **The figure connects energy sources with human activities using a set of "pipes" of different widths and colors.**
   a. Does the color of a pipe on the left side of the figure represent an energy source or a human activity?
   b. Why is the width of the pipe connecting "coal" to "electric power generation" about twice as wide as the one connecting "nuclear power" to "electric power generation"?
2. **What determines the width of the yellow and blue arrows that point from the boxes representing human activities?**
3. **Why is the arrow pointing upward from "electric power generation" wider than the arrows pointing upward from the other human-activity boxes?**
4. **Compute answers to the following questions from the numerical data on the figure:**
   a. What fraction of U.S. energy production came from fossil fuels?
   b. Which activity consumed more energy, electrical power generation or transportation?
   c. What fraction of the total energy production was wasted?
   d. How much carbon did the U.S. energy system emit in 2017?