2. Suppose that you would like to make your own lifestyle carbon-neutral. You plan to begin by reducing the emissions you are responsible for by 25%. What three actions would you take first to achieve your goal?
3. How might your campus reduce its greenhouse gas emissions? Come up with three concrete proposals for ways to reduce emissions on your campus that you feel would be effective and feasible. How would you present these proposals to campus administrators to gain their support?
4. **CASE STUDY CONNECTION** You are the city manager for a coastal U.S. city that scientists predict will be hit hard by sea level rise, with risks and impacts trailing those in Miami by just a few years. You have just returned from a professional conference in Florida, where you toured Miami Beach and learned of the efforts being made there to adapt to climate change. What steps would you take to help your own city prepare for rising sea level? How would you explain the risks and impacts of climate change to your fellow city leaders to gain their support? Of the measures being taken in Florida communities, which would you choose to study closely, which would you want to begin right away, and which would be highest priority in the long run? Explain your choices.
5. **THINK IT THROUGH** You have just been elected governor of a medium-sized U.S. state. Polls show that the public wants you to take action to reduce greenhouse gas emissions, but does not want prices of gasoline or electricity to rise. Your state legislature will support you in your efforts as long as you remain popular with voters. One neighboring state has just passed ambitious legislation mandating steep greenhouse gas emissions reductions. Another neighboring state has recently joined a new regional emissions trading consortium. A third neighboring state has just established a revenue-neutral carbon tax. A fourth neighboring state is spending millions of dollars building seawalls around its coastal cities. What actions will you take in your first year as governor?
6. **THINK IT THROUGH** You have been appointed as the U.S. representative to an international conference to negotiate terms of an emissions reduction treaty that would build upon or replace the Paris Agreement. The U.S. government has instructed you to take a leading role in designing the new treaty and to engage constructively with other nations' representatives while protecting America's economic and political interests. What type of agreement will you try to shape? Describe at least three components that you would propose or agree to, and at least one that you would oppose.

CALCULATING Ecological Footprints

Global climate change is something to which we all contribute, because fossil fuel combustion plays such a large role in supporting the lifestyles we lead. Conversely, as individuals, each one of us can help to address climate change through personal decisions and actions in how we live our lives.

Several online calculators enable you to calculate your own personal carbon footprint, the amount of carbon emissions for which you are responsible. Go to www.nature.org/greenliving/carboncalculator/ or to www.carbonfootprint.com/calculator.aspx, take the quiz, and enter the relevant data in the table.

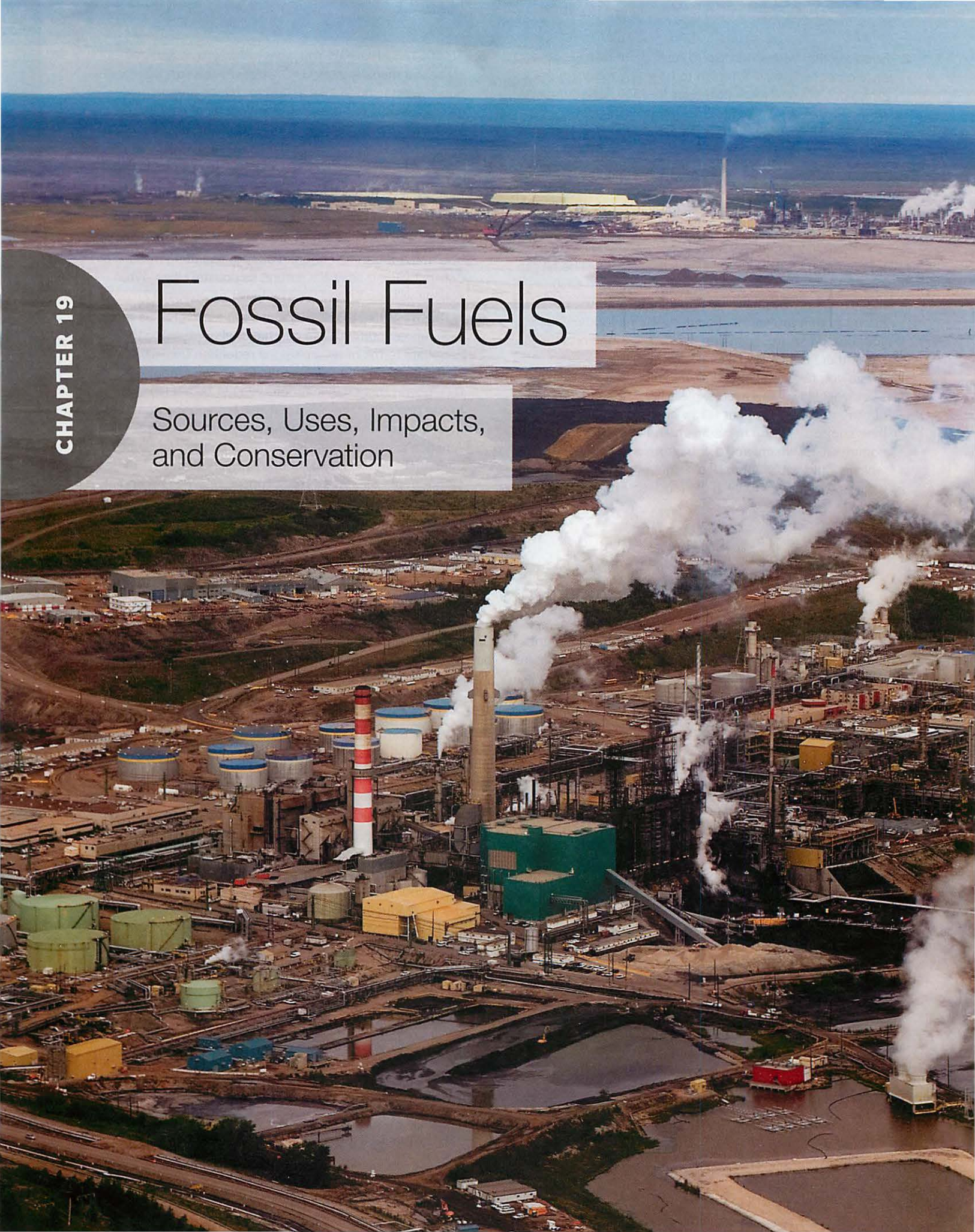
	CARBON FOOTPRINT (TONS PER PERSON PER YEAR)
World average	
U.S. average	
Your footprint	
Your footprint with three changes (see Question 3)	

1. How does your personal carbon footprint compare to that of the average U.S. resident? How does it compare to that of the average person in the world? Why do you think your footprint differs in the ways it does?
2. As you took the quiz and noted the impacts of various choices and activities, which one surprised you the most?
3. Think of three changes you could make in your lifestyle that would lower your carbon footprint. Now take the footprint quiz again, incorporating these three changes. Enter your resulting footprint in the table. By how much did you reduce your yearly emissions?
4. What do you think would be an admirable yet realistic goal for you to set as a target value for your own footprint? Would you choose to purchase carbon offsets to help reduce your impact? Why or why not?

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CHAPTER 19

Fossil Fuels

Sources, Uses, Impacts, and Conservation

central
CASE STUDY

Alberta's Oil Sands and the Keystone XL Pipeline



> **The president's veto of the bipartisan Keystone bill represents a defeat for jobs, infrastructure, and the middle class.**
> Senate Majority Leader Mitch McConnell (R-Kentucky)

> **If Canada proceeds, and we do nothing, it will be game over for the climate.**
> Climate scientist James Hansen

Everything relating to Canada's oil sands is huge. These fossil fuel deposits cover a region the size of Illinois, within boreal forests that span the width of the continent. Open pits miles wide are dug to extract the fuel. Inside these gargantuan pits, million-pound haul trucks with tires 14 feet wide and shovels five stories high look like ants when viewed from the rim of the pit. The economic value of the extracted oil is astounding. And the impacts of putting the oil to use are huge, as well: Burning all this fuel would alter the very climate of our planet.

Oil sands, also called **tar sands,** are layers of sand or clay saturated with a viscous, tarry type of petroleum called *bitumen*. Huge areas of these wet blackish deposits underlie a thinly populated region of northern Alberta, and the implications of mining them for oil are momentous. To some people the oil sands represent wealth and security, a key to maintaining our fossil-fuel-based lifestyle far into the future. To others they threaten appalling pollution and a severe disruption of Earth's climate.

To extract oil from oil sands, companies clear the forest and then strip-mine the land, creating open pits 215 m (400 ft) deep. The gooey deposits are mixed with hot water and chemicals to separate the bitumen from the sand, and the bitumen is removed and processed. Wastewater is dumped into toxic tailings lakes that are even larger than the mines. Where oil sands are located more deeply underground, hot water is injected down shafts to liquefy, separate, and extract the bitumen in place.

Mining for oil sands began in Alberta in 1967, but for many years it was hard to make money extracting these low-quality deposits. Rising oil prices after 2003 turned it into a profitable venture, and dozens of companies rushed in. Canadian oil sands became the source of up to 2.3 million barrels of oil per day, making up most of Canada's petroleum extraction, and each truckload that left a mine carried bitumen containing close to $20,000 in oil.

In 2015, a sharp downturn in world oil prices slowed the rush, but most companies continued mining, counting on profits from higher future prices to cover their short-term losses. Indeed, there is plenty left for the future; thanks to the oil sands, Canada boasts the world's third-largest proven reserves of oil, after Venezuela and Saudi Arabia.

Canada looked for buyers south of its border first, and the TransCanada Corporation built the Keystone



Protesting the Keystone XL pipeline at the U.S. White House

Upon completing this chapter, you will be able to:

- Identify the energy sources that we use
- Discuss the value of the EROI concept
- Describe the formation of major types of fossil fuels
- Explain how we extract, process, and use fossil fuels
- Assess concerns over the future decline of conventional oil supplies
- Outline ways in which we are extending our reach for fossil fuels
- Examine environmental impacts of fossil fuel use, and explore ways to minimize these impacts
- Assess political, social, and economic aspects of fossil fuel use
- Discuss strategies for conserving energy and enhancing efficiency

An oil sands processing facility in Alberta, Canada

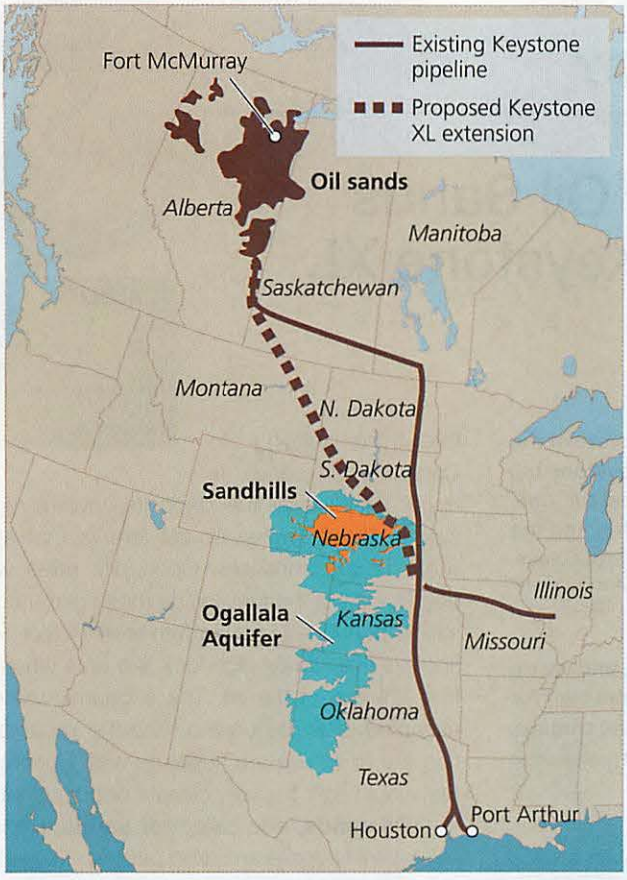


FIGURE 19.1 The Keystone pipeline system brings bitumen from Alberta's oil sands into the United States. The proposed Keystone XL extension (dashed line) set off a complex debate.

Pipeline to ship diluted bitumen into the United States. This pipeline system began operating in 2010, bringing oil from Alberta nearly 3500 km (2200 mi) to Illinois and Oklahoma (**FIGURE 19.1**). An extension later conveyed the oil to refineries on the Texas coast. TransCanada then proposed the Keystone XL extension, a 1400-km (875-mi) stretch of larger-diameter pipeline that would cut across the Great Plains to shave off distance and add capacity to the existing system. This proposed shortcut leg would also transport oil from the newly productive fields of the Bakken Formation in North Dakota and Montana.

The Keystone XL pipeline proposal soon met opposition from people living along the proposed route who were concerned about health, environmental protection, and property rights. It also faced nationwide opposition from advocates of action to address global climate change.

Pipeline proponents argued that the Keystone XL project would create jobs for workers in the U.S. heartland and would guarantee a dependable oil supply for decades to come. They stressed that buying oil from Canada—a stable, friendly, democratic neighbor—could help end U.S. reliance on oil-extracting nations such as Saudi Arabia and Venezuela that have authoritarian governments and poor human rights records.

Opponents of the pipeline extension expressed dismay at the destruction of boreal forest and anxiety about transporting oil above the continent's largest aquifer, where spills could contaminate drinking water for millions of people and irrigation water for America's breadbasket. They pointed out that most of the oil would be destined for export, and not for use in the United States. Most of all, they sought to avoid extracting a vast new source of fossil fuels whose combustion would release immense amounts of greenhouse gases and intensify climate change. By encouraging a source of oil that is energy-intensive to extract and that burns less cleanly than conventional fuels, they maintained, the United States would prolong fossil fuel dependence and worsen climate change, when it should instead be transitioning to clean renewable energy.

Under pressure from all sides, the administration of U.S. President Barack Obama walked a fine line. Because the proposed Keystone XL pipeline would cross an international border, it required a presidential permit from the U.S. Department of State. Because of concerns about damage to the ecologically sensitive Sandhills area of Nebraska and potential contamination of the Ogallala Aquifer, the State Department asked TransCanada to revise its proposed route to avoid the areas of concern. In 2014, the State Department released its final environmental impact statement for the new route. It concluded that encouraging oil sands extraction by building Keystone XL would increase greenhouse gas pollution—yet that if the pipeline was *not* built, Canada would likely find other ways to extract and sell its oil, including transporting it by rail, which presents its own set of risks (p. 533).

As the public debate intensified during the seven years of the project's review, tens of thousands of Americans protested against the pipeline in front of the White House. These protestors viewed the decision on Keystone XL as a crucial test of Obama's vow to deal with climate change. In contrast, business interests and many Republicans in Congress objected furiously to the administration's hesitancy to approve the pipeline, arguing that an economic opportunity was slipping by. In 2015 the Republican-led Congress voted to approve construction of Keystone XL. Obama vetoed the measure, maintaining that the decision legally rested with the executive branch.

In November 2015, President Obama decided against approving the Keystone XL pipeline, and told the nation that his administration had judged that the pipeline "would not serve the national interest of the United States." The pipeline's importance had been "overinflated," he stated, and its construction would not contribute meaningfully to the U.S. economy, would not lower gas prices for consumers, and would not enhance America's energy security. Moreover, he noted, approving it on the eve of global climate talks in Paris (p. 507) would undercut U.S. leadership just as America sought to gather nations together to address climate change.

Obama's decision on Keystone XL did not end the broader debate over the role of fossil fuels in our economy. Indeed, the divergent views on Canada's oil sands reflect our confounding relationship with fossil fuels. These energy sources power our civilization and have enabled our modern standard of living—yet as climate change worsens, we face the need to wean ourselves from them and shift to clean renewable energy sources. The way in which we handle this complex transition will determine a great deal about the quality of our lives and the future of our society and our planet.

Sources of Energy

Humanity has devised many ways to harness the renewable and nonrenewable forms of energy available on our planet (TABLE 19.1). We use these energy sources to heat and light our homes; power our machinery; fuel our vehicles; produce plastics, pharmaceuticals, and synthetic fibers; and provide the many comforts and conveniences to which we've grown accustomed.

Nature offers us a variety of energy sources

Most of Earth's energy comes from the sun. We can harness energy from the sun's radiation directly by using solar power technologies. Solar radiation also helps drive wind and the water cycle, enabling us to harness wind power and hydroelectric power. And, of course, sunlight drives photosynthesis (p. 30) and the growth of plants, from which we take wood and other biomass as a fuel source. When plants and other organisms die and are buried in sediments under particular conditions, their stored chemical energy may eventually be incorporated into **fossil fuels,** highly combustible substances formed from the remains of organisms from past geologic ages. We rely on three main fossil fuels, in the form of a solid (coal), liquid (oil), and gas (natural gas).

In addition, a great deal of energy emanates from Earth's core, making geothermal power available for our use. Energy also results from the gravitational pull of the moon and sun, which powers ocean tides. Finally, an immense amount of energy resides within the bonds among protons and neutrons in atoms, and this energy provides us with nuclear power. (We explore all these energy sources as alternatives to fossil fuels in Chapters 20 and 21.)

Energy sources such as sunlight, geothermal energy, and tidal energy are considered perpetually renewable because they are readily replenished, so we can keep using them without depleting them (p. 4). In contrast, energy sources such as coal, oil, and natural gas are considered nonrenewable. These nonrenewable fuels result from ongoing natural processes, but it takes so long for fossil fuels to form that, once depleted, they cannot be replaced within any time span useful to our civilization. It takes a thousand years for the biosphere to generate the amount of organic matter that must be buried to transform into a single day's worth of fossil fuels for our society. To replenish the fossil fuels we have depleted so far would take many millions of years. At our rising rate of consumption, we will use up Earth's easily accessible store of conventional fossil fuels in just decades. For this reason, and because fossil fuels exert severe environmental impacts, renewable energy sources increasingly are being developed as alternatives to fossil fuels.

TABLE 19.1 Energy Sources We Use

ENERGY SOURCE	DESCRIPTION	TYPE OF ENERGY
Coal	Fossil fuel extracted from ground (solid)	Nonrenewable
Oil	Fossil fuel extracted from ground (liquid)	Nonrenewable
Natural gas	Fossil fuel extracted from ground (gas)	Nonrenewable
Nuclear energy	Energy from atomic nuclei of uranium	Nonrenewable
Biomass energy	Energy stored in plant matter from photosynthesis	Renewable
Hydropower	Energy from running water	Renewable
Solar energy	Energy from sunlight directly	Renewable
Wind energy	Energy from wind	Renewable
Geothermal energy	Earth's internal heat rising from core	Renewable
Tidal and wave energy	Energy from tides and ocean waves	Renewable

We rely mostly on fossil fuels

Since the industrial revolution, fossil fuels have replaced biomass as our society's dominant source of energy. Global consumption of coal, oil, and natural gas has risen for years and is now at its highest level ever (FIGURE 19.2). We have favored fossil fuels as an energy source because their high energy content makes them efficient to burn, ship, and store. A single gallon of oil contains as much energy as a person would expend in nearly 600 hours of human labor.

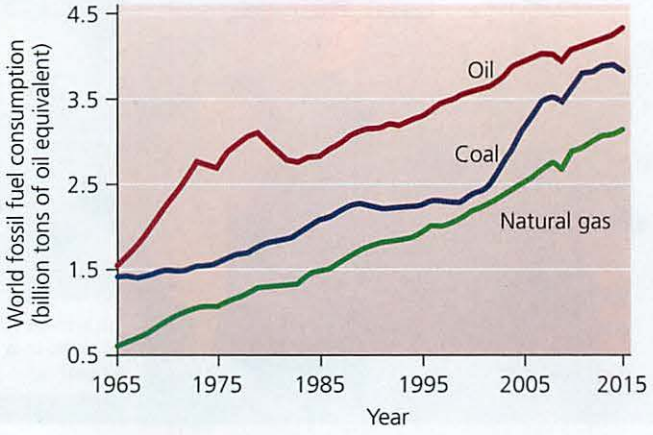


FIGURE 19.2 Annual global consumption of fossil fuels has risen greatly over the past 50 years. Oil remains our leading energy source. *Data from BP p.l.c., 2016.* Statistical review of world energy 2016.

DATA By roughly what percentage has the annual consumption of oil risen since the year you were born? Which fuel has risen fastest since you were born—oil, coal, or natural gas?

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We use fossil fuels for transportation, manufacturing, heating, and cooking, and also to generate **electricity,** a secondary form of energy that is convenient to transfer over long distances and apply to a variety of uses. Each type of fuel has its own mix of uses, and each contributes in different ways to our economies and our daily needs. For instance, oil is used mostly for transportation, whereas coal is used mostly to generate electricity.

Energy is unevenly distributed

Some regions of the globe have substantial reserves of coal, oil, or natural gas, whereas others have very few. Half the world's proven reserves of crude oil lie in the Middle East. The Middle East is also rich in natural gas, as is Russia. The United States possesses the most coal of any nation (TABLE 19.2).

Rates at which we consume energy also vary from place to place. A world map of per-person consumption shows that people in developed regions generally consume far more energy than do people of developing regions (FIGURE 19.3). Per person, the most industrialized nations use more than 50 times more energy than do the least industrialized nations. As an example, the United States has only 4.4% of the world's population, but it consumes nearly 18% of the world's energy.

Societies differ in how they use energy, as well. Industrialized nations apportion roughly one-third to transportation, one-third to industry, and one-third to all other uses. In contrast, industrializing nations devote more energy to subsistence activities such as growing and preparing food and heating homes. Moreover, people in developing countries often rely on manual or animal energy sources instead of automated ones. For instance, most rice farmers in Southeast Asia plant rice by hand, but industrial rice growers in California use airplanes. Because industrialized nations rely more on mechanized equipment and technology, they use more

TABLE 19.2 Nations with the Largest Proven Reserves of Fossil Fuels

COAL (% world reserves)		OIL (% world reserves)		NATURAL GAS (% world reserves)	
United States	26.6	Venezuela*	17.5	Iran	18.2
Russia	17.6	Saudi Arabia	15.7	Russia	17.3
China	12.8	Canada*	10.1	Qatar	13.1
Australia	8.6	Iran	9.3	Turkmenistan	9.4
India	6.8	Iraq	8.4	United States	5.6

*Most reserves in Venezuela and Canada consist of oil sands, which are included in these figures.
Data from BP p.l.c., 2016. *Statistical review of world energy 2016.*

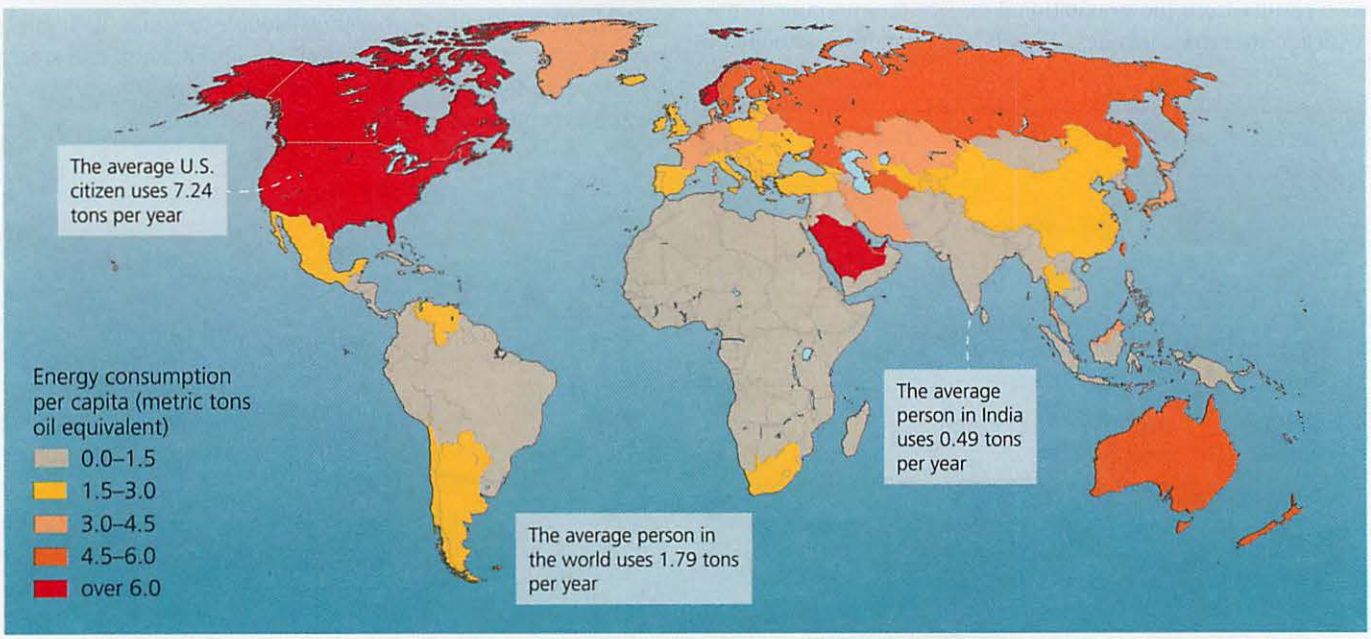


FIGURE 19.3 People in wealthy industrialized nations tend to consume the most energy per person. This map combines all types of energy, standardized to metric tons of "oil-equivalent" (the amount of fuel needed to result in the energy gained from burning one metric ton of crude oil). *Data from BP p.l.c., 2015.* Statistical review of world energy 2015.

DATA How many times more energy does the average U.S. citizen use than the average person in the world? How many times more energy does the average U.S. citizen use than the average citizen of India?

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fossil fuels. In the United States, oil, coal, and natural gas together supply 82% of energy demand (FIGURE 19.4).

It takes energy to make energy

We do not simply get energy for free. To harness, extract, process, and deliver energy, we need to invest substantial inputs of energy. For instance, mining oil sands in Alberta requires using powerful vehicles and heavy machinery, as well as constructing an immense infrastructure of roads, pipelines, waste ponds, storage tanks, water intakes, processing facilities, housing for workers, and more—all requiring the use of energy. Natural gas must be burned to heat the water that is used to separate the bitumen from the sand. Processing and piping the oil away from the extraction site, and then refining it into products we can use, require further energy inputs. Thus, when evaluating an energy source, it is important to subtract costs in energy invested from the benefits in energy received. **Net energy** expresses the difference between energy returned and energy invested:

$$\text{Net energy} = \text{Energy returned} - \text{Energy invested}$$

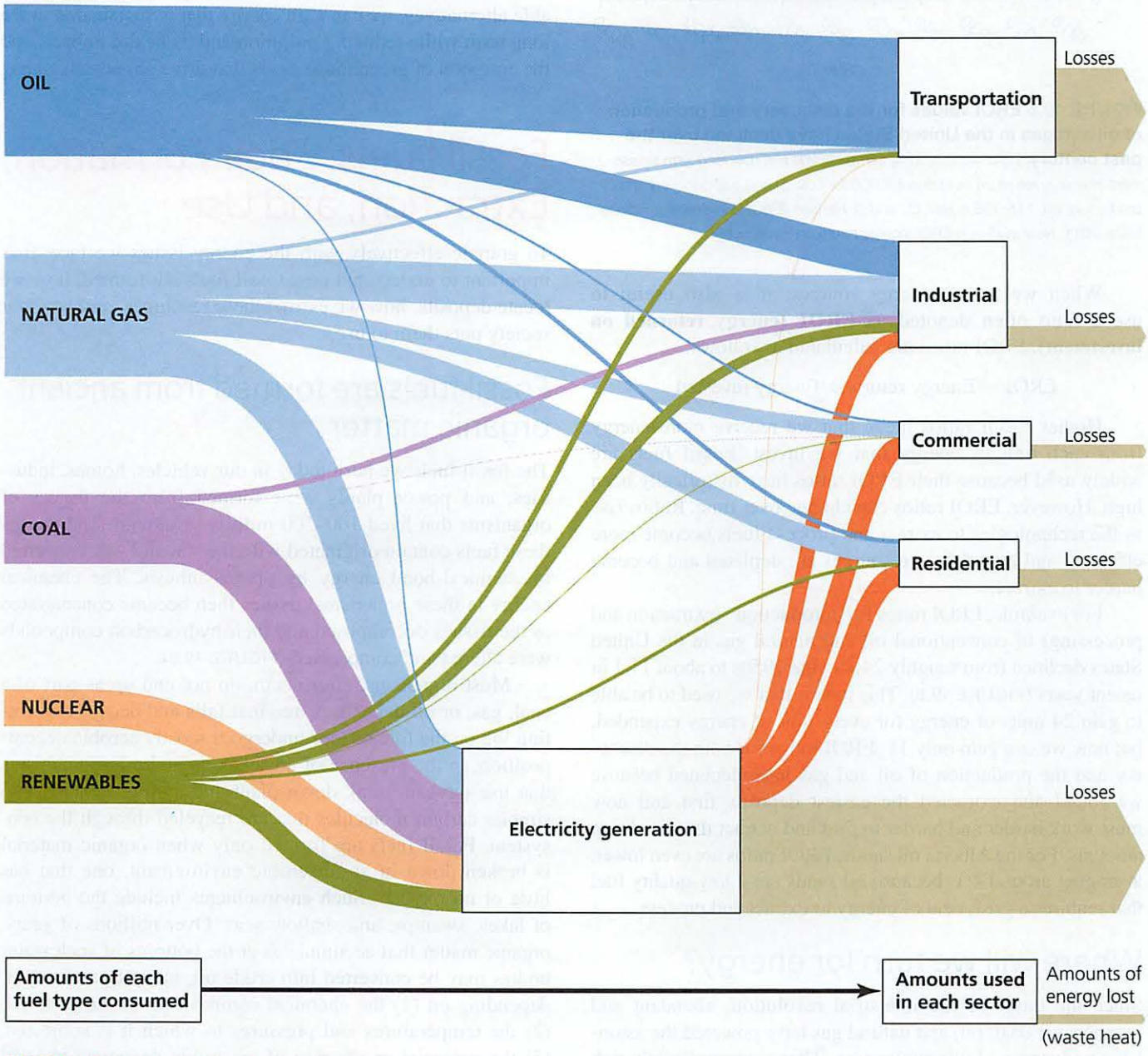


FIGURE 19.4 Total energy flow of the United States. Amounts are represented by the thickness of each bar. Energy consumed (domestic extraction plus imports minus exports) is shown on the left, and destinations of this energy are shown on the right. Portions of each energy source are used directly in the residential, commercial, industrial, and transportation sectors. Other portions are used to generate electricity, which in turn powers these sectors. The large amounts of energy lost as waste heat are shown on the right. *Adapted from Lawrence Livermore National Laboratory. Data are for 2015, from U.S. Energy Information Administration.*

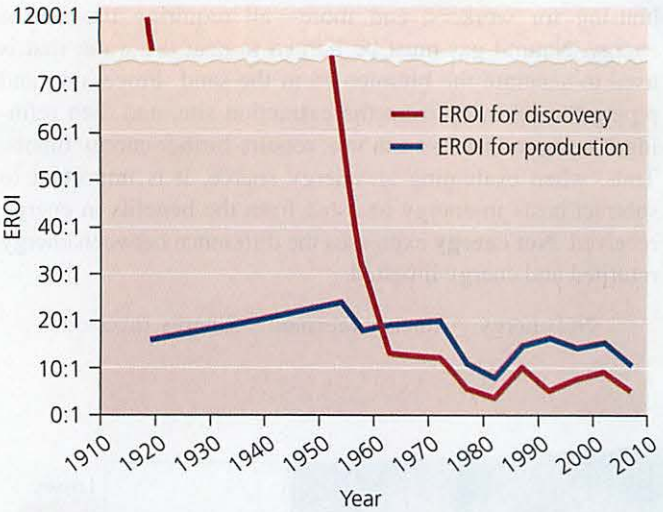


FIGURE 19.5 EROI values for the discovery and production of oil and gas in the United States have declined over the past century. *Data from Guilford, M., et al., 2011. A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production. pp. 115–136 in Hall, C., and D. Hansen (Eds.),* Sustainability, Special Issue, 2011, New studies in EROI (energy return on investment).

When we assess energy sources, it is also useful to use a ratio often denoted as **EROI (energy returned on investment).** EROI ratios are calculated as follows:

$$\text{EROI} = \text{Energy returned}/\text{Energy invested}$$

Higher EROI ratios mean that we receive more energy from each unit of energy that we invest. Fossil fuels are widely used because their EROI ratios have historically been high. However, EROI ratios can change over time. Ratios rise as the technologies to extract and process fuels become more efficient, and they fall as resources are depleted and become harder to extract.

For example, EROI ratios for "production" (extraction and processing) of conventional oil and natural gas in the United States declined from roughly 24:1 in the 1950s to about 11:1 in recent years (FIGURE 19.5). This means that we used to be able to gain 24 units of energy for every unit of energy expended, but now we can gain only 11. EROI ratios for both the discovery and the production of oil and gas have declined because we found and extracted the easiest deposits first and now must work harder and harder to find and extract the remaining amounts. For the Alberta oil sands, EROI ratios are even lower, averaging around 4:1, because oil sands are a low-quality fuel that requires a great deal of energy to extract and process.

Where will we turn for energy?

Since the onset of the industrial revolution, abundant and inexpensive coal, oil, and natural gas have powered the astonishing advances of our civilization. These extraordinarily rich sources of energy have helped to bring us a standard of living our ancestors could scarcely have imagined. Yet because fossil fuel deposits are finite and nonrenewable, easily accessible supplies of the three main fossil fuels have dwindled, and EROI ratios have fallen.

In response, today we are devoting enormous amounts of money, energy, and technology to extend our reach for fossil fuels. We are using potent new extraction methods to free gas and oil tightly bound in rock layers. We are deploying powerful new machinery and techniques to squeeze more fuel from sites that were already extracted. We are drilling deeper underground, farther offshore, and into the Arctic seabed. And we are pursuing new types of fossil fuels, such as Alberta's oil sands.

There is, however, a different way we can respond to the ongoing depletion of conventional fossil fuel resources: We can hasten the development of clean and renewable energy sources to replace them. By transitioning to clean and renewable alternatives, we can gain energy that is sustainable in the long term while reducing pollution and its health impacts and the emission of greenhouse gases that drive climate change.

Fossil Fuels: Their Formation, Extraction, and Use

To grapple effectively with the energy issues we face, it is important to understand how fossil fuels are formed, how we locate deposits, how we extract these resources, and how our society puts them to use.

Fossil fuels are formed from ancient organic matter

The fossil fuels we burn today in our vehicles, homes, industries, and power plants were formed from the tissues of organisms that lived 100–500 million years ago. The energy these fuels contain originated with the sun and was converted to chemical-bond energy by photosynthesis. The chemical energy in these organisms' tissues then became concentrated as the tissues decomposed and their hydrocarbon compounds were altered and compressed (FIGURE 19.6).

Most organisms, after death, do not end up as part of a coal, gas, or oil deposit. A tree that falls and decays as a rotting log on the forest floor undergoes mostly aerobic decomposition; in the presence of air, bacteria and other organisms that use oxygen break down plant and animal remains into simpler carbon molecules that are recycled through the ecosystem. Fossil fuels are formed only when organic material is broken down in an anaerobic environment, one that has little or no oxygen. Such environments include the bottoms of lakes, swamps, and shallow seas. Over millions of years, organic matter that accumulates at the bottoms of such water bodies may be converted into crude oil, natural gas, or coal, depending on (1) the chemical composition of the material, (2) the temperatures and pressures to which it is subjected, (3) the presence or absence of anaerobic decomposers, and (4) the passage of time.

Because fossil fuels form only under certain conditions, they occur in isolated deposits. For example, Alberta's oil sands hold rich reserves of oil that surrounding regions do not. Geologists searching for fossil fuels drill cores and conduct

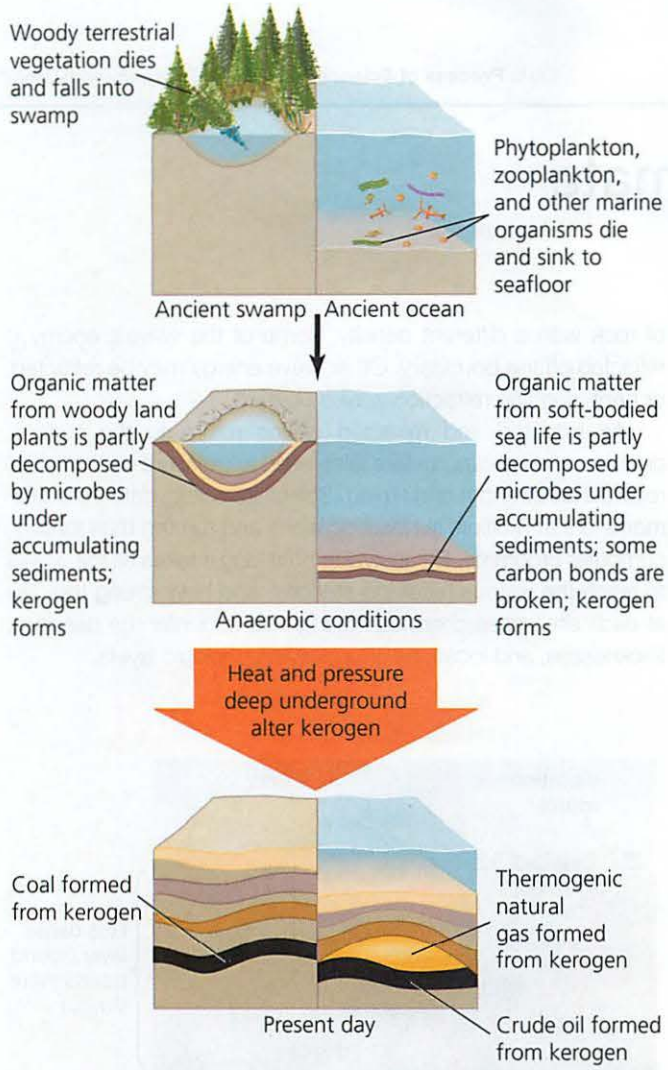


FIGURE 19.6 Fossil fuels form after organisms die and end up in oxygen-poor conditions. This can occur when trees fall into lakes and are buried by sediment or when phytoplankton and zooplankton drift to the seafloor and are buried (**top**). Organic matter that undergoes slow anaerobic decomposition deep under sediments forms kerogen (**middle**). Coal results when plant matter is compacted so tightly that little decomposition occurs (**bottom left**). Geothermal heating may turn kerogen into crude oil and natural gas (**bottom right**), which come to reside in porous rock layers beneath dense, impervious layers.

ground, air, and seismic surveys to map underground rock formations and predict where fossil fuel deposits might occur (see **THE SCIENCE BEHIND THE STORY**, pp. 522–523).

Coal

Coal is a hard blackish substance formed from organic matter (generally woody plant material) compressed under very high pressure, creating dense, solid carbon structures (**FIGURE 19.7**). Coal typically results when water is squeezed out of such material as pressure and heat increase over time, and when little decomposition takes place. The proliferation 300–400 million years ago of swamps where organic material was buried created coal deposits in many regions of the world.

Coal varies from deposit to deposit in the amount of water, carbon, and potential energy it contains. Organic material that is broken down anaerobically but remains moist and near the surface is called *peat*. As peat decomposes further, as it is buried under sediments, as heat and pressure increase, and as time passes, moisture is squeezed out and carbon compounds compress more tightly together, forming coal. The more coal is compressed, the denser is its carbon content and the greater is its energy content per unit volume.

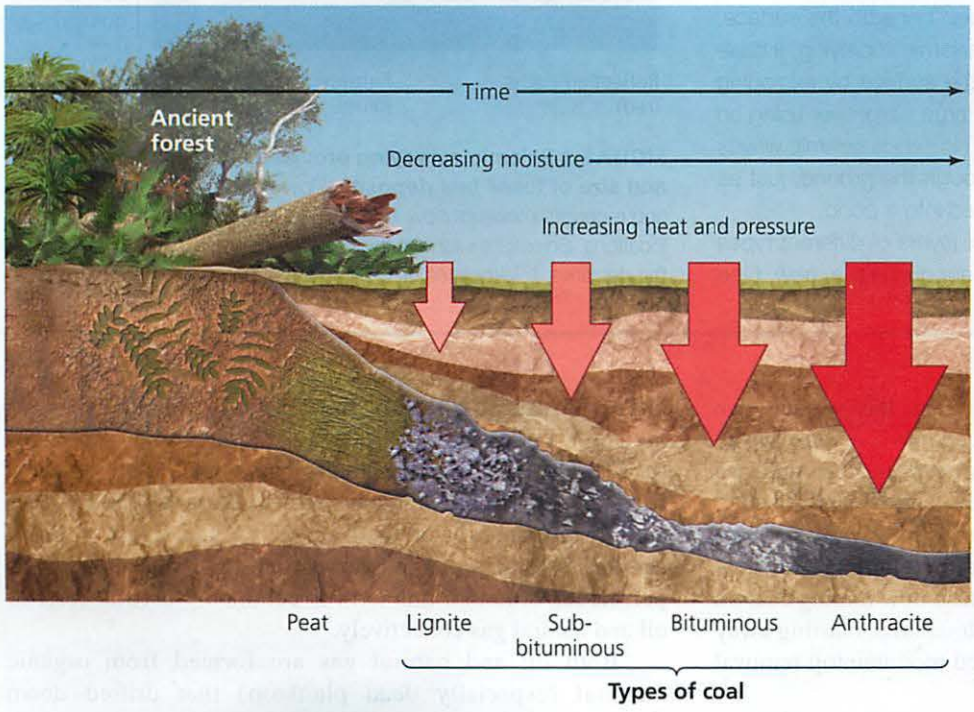
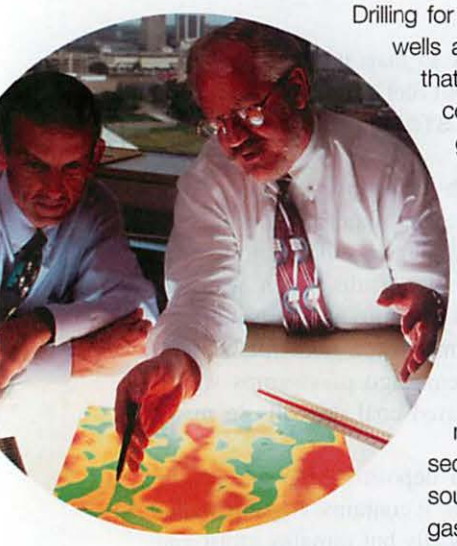


FIGURE 19.7 Coal forms as ancient plant matter turns to peat and then is compressed underground. Of the four classes of coal, anthracite coal is formed under the greatest pressure, where temperatures are high and moisture content is low. Anthracite coal has the densest carbon content and so contains the most potential energy.

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How Do We Find and Estimate Fossil Fuel Deposits?



Petroleum geologists study mapped seismic data to determine where oil or gas might be found.

Drilling for oil or gas is risky business: Most wells are unproductive, and a company that doesn't pick its spots effectively could soon go bankrupt. So oil and gas companies turn to scientists to help them figure out where to drill.

The industry employs petroleum geologists who study underground rock formations to predict where deposits of oil and natural gas might lie. Because the organic matter that gave rise to fossil fuels was buried in sediments, geologists know to look for sedimentary rock that may act as a source. They also know that oil and gas tend to seep upward through porous rock until being trapped by impermeable layers.

To map subsurface rock layers, petroleum geologists first survey the landscape on the ground and from airplanes, studying rocks on the surface. Because rock layers often become tilted over geologic time, these strata may protrude at the surface, giving geologists an informative "side-on" view.

But to really understand what's deep beneath the surface, scientists conduct seismic surveys. In seismic surveying, a base station creates powerful vibrations at the surface by exploding dynamite, thumping the ground with a large weight, or using an electric vibrating machine (**FIGURE 1**). This sends seismic waves down and outward in all directions through the ground, just as ripples spread when a pebble is dropped into a pond.

As they travel, the waves encounter layers of different types of rock. Each time a seismic wave encounters a new type of rock with a different density, some of the wave's energy is reflected off the boundary. Other wave energy may be refracted, or bent, sending refraction waves upward.

As reflected and refracted waves return to the surface, devices called seismometers (also used to measure earthquakes) record their strength and timing. Scientists collect data from seismometers at multiple surface locations and run the data through computer programs. By analyzing how long it takes all the waves to reach the various receiving stations, and how strong they are at each site, researchers can triangulate and infer the densities, thicknesses, and locations of underlying geologic layers.

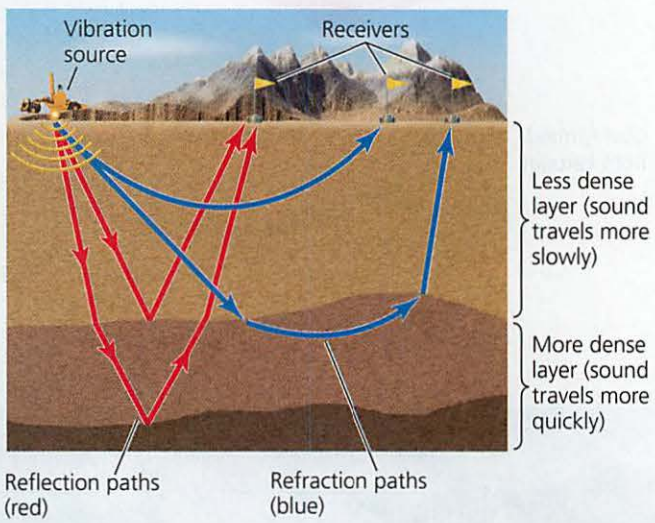


FIGURE 1 Seismic surveying provides clues to the location and size of fossil fuel deposits. Powerful vibrations are created, and receivers measure how long it takes seismic waves to reach other locations. Scientists interpret the patterns of wave reception to infer the densities, thicknesses, and locations of underlying rock layers.

To extract coal from deposits near the surface, we use strip mining, in which heavy machinery scrapes away huge amounts of earth. For deposits deep underground, we use subsurface mining, digging vertical shafts and blasting out networks of horizontal tunnels to follow seams, or layers, of coal. (Strip mining and subsurface mining are illustrated in Figure 23.7, p. 635.) We are also now mining coal on immense scales in the Appalachian Mountains, blasting away entire mountaintops in a process called mountaintop removal mining (pp. 530, 639).

Oil and natural gas The thick blackish liquid we know as **oil** consists of a mix of many types of hydrocarbon molecules (p. 27). The term **crude oil** refers specifically to oil extracted from the ground before it is refined. **Natural gas** is a gas consisting primarily of methane (CH_4) and lesser, variable amounts of other volatile hydrocarbons. Oil is also known as **petroleum,** although this term is commonly used to refer to oil and natural gas collectively.

Both oil and natural gas are formed from organic material (especially dead plankton) that drifted down

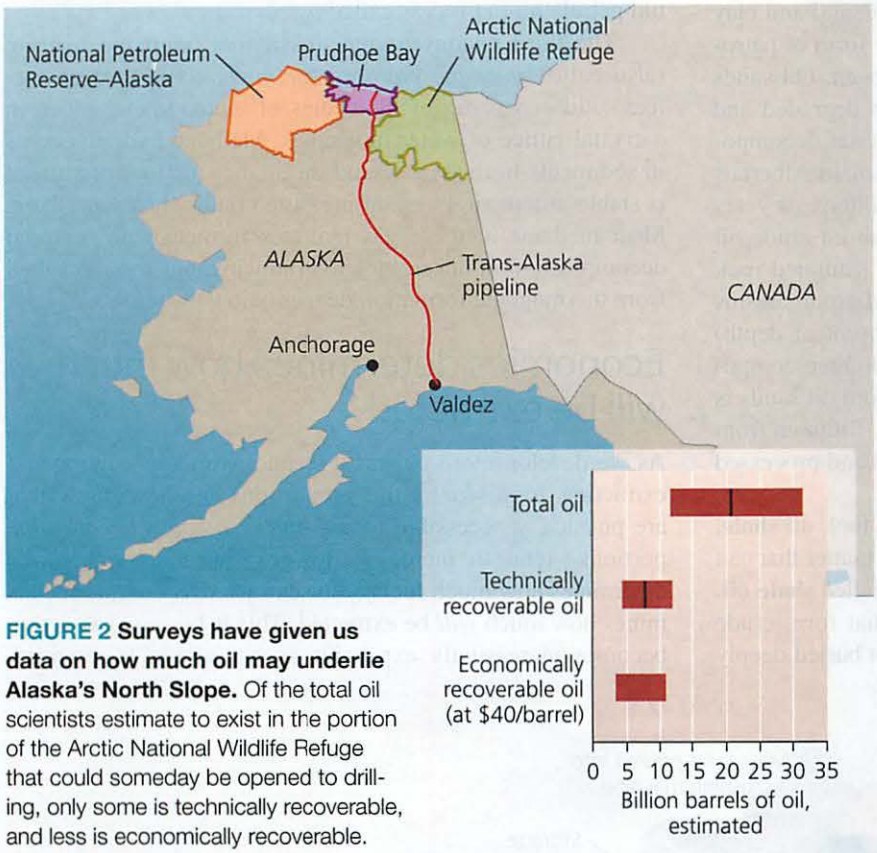


FIGURE 2 Surveys have given us data on how much oil may underlie Alaska's North Slope. Of the total oil scientists estimate to exist in the portion of the Arctic National Wildlife Refuge that could someday be opened to drilling, only some is technically recoverable, and less is economically recoverable.
Data from U.S. Geological Survey.

Seismic surveying is similar to how we use sonar in water or how bats use echolocation as they fly. It is also used for finding coal deposits, salt and mineral deposits, and geothermal energy hotspots, as well as for studying faults, aquifers, and engineering sites.

Using data from such techniques, geologists with the U.S. Geological Survey (USGS) in 1998 assessed the subsurface geology of the Arctic National Wildlife Refuge on Alaska's North Slope to predict how much oil it may hold (**FIGURE 2**). Over three years, dozens of scientists conducted fieldwork and combined their results with a reanalysis of 2300 km (1400 mi) of seismic survey data that industry had collected in the 1980s.

After studying their resulting subsurface maps, USGS scientists concluded, with 95% certainty, that between 11.6 and 31.5 billion barrels of oil lay underneath the region of the refuge that Congress has debated opening for drilling. The mean estimate of 20.7 billion barrels is enough to supply the United States for 3 years at its current rate of consumption.

However, some portion of oil from any deposit is impossible to extract using current technology, so geologists estimate technically recoverable amounts of fuels. In its estimate for the Arctic Refuge, the USGS calculated technically recoverable oil to total 4.3–11.8 billion barrels, with a mean estimate of 7.7 billion barrels (just more than 1 year of U.S. consumption).

The portion of this oil that is economically recoverable depends on the costs of extracting it and the price of oil on the world market. USGS scientists calculated that at a price of $40 per barrel, 3.4–10.8 billion barrels would be economically worthwhile to recover. At higher prices, the economically recoverable amount would be closer to the technically recoverable amount.

In 2002, the USGS conducted similar analyses for the National Petroleum Reserve–Alaska, a vast parcel of tundra to the west of the Arctic Refuge and Prudhoe Bay that the U.S. government set aside 90 years ago as an emergency reserve of petroleum. USGS scientists estimated that this region contained 9.3 billion barrels of technically recoverable oil.

Across the world, petroleum geologists are using similar methods to try to determine how much oil remains to extract. Their work is of vital importance as the world's nations struggle to pursue well-informed energy policies.

through coastal marine waters millions of years ago and became buried in sediments on the ocean floor. This organic material was transformed by time, heat, and pressure into today's natural gas and crude oil. Natural gas may form directly, or it may form from coal or oil altered by heating. As a result, natural gas is often found above deposits of oil or seams of coal, and is often extracted along with those fuels.

Underground pressure tends to drive oil and natural gas upward through cracks and fissures in porous rock until they become trapped under a dense, impermeable rock layer. Oil and gas companies employ geologists to study rock formations to identify promising locations. Once a location is identified, a company conducts exploratory drilling, drilling small holes to great depths. If enough oil or gas is encountered, extraction may begin. Because oil and gas are under pressure while in the ground, they rise to the surface when a deposit is tapped. Once pressure is relieved and some portion has risen to the surface, the remainder will need to be pumped out.

Unconventional fossil fuels Besides the three conventional fossil fuels—coal, oil, and natural gas—other types of fossil fuels exist, often called "unconventional" because we are not (yet) using them as widely. Three examples of unconventional fossil fuels are oil sands, oil shale, and methane hydrate.

As we've seen, oil sands consist of moist sand and clay containing 1–20% bitumen, a thick and heavy form of petroleum that is rich in carbon and poor in hydrogen. Oil sands result from crude oil deposits that have been degraded and chemically altered by water erosion and bacterial decomposition. The leading scientific hypothesis to explain Alberta's oil sands is that geologic changes tens of millions of years ago as the Rocky Mountains were uplifted caused crude oil to migrate northeastward and upward until it saturated rock and soil in what is now northeastern Alberta. Microorganisms (which are abundant near the surface but absent at depth) began to consume the oil, particularly the lighter components, leaving degraded heavy bitumen. Oil from oil sands is extracted by two main methods (FIGURE 19.8). Bitumen from either process must then be chemically refined and processed to create synthetic crude oil (called *syncrude*).

The second type of unconventional fossil fuel, **oil shale,** is sedimentary rock (p. 35) filled with organic matter that can be processed into a liquid form of petroleum called **shale oil.** Oil shale is formed by the same processes that form crude oil but occurs when the organic matter was not buried deeply enough or subjected to enough heat and pressure to form oil. Oil shale is extracted using strip mines or subsurface mines. It can be burned directly like coal, or it can be processed in several ways. One way to process oil shale is to bake it in the presence of hydrogen and in the absence of air to extract liquid petroleum (a process called *pyrolysis*).

The third unconventional fossil fuel, **methane hydrate** (also called *methane clathrate* or *methane ice*), is an ice-like solid consisting of molecules of methane embedded in a crystal lattice of water molecules. Methane hydrate occurs in sediments in the Arctic and on the ocean floor because it is stable at temperature and pressure conditions found there. Most methane in these gas hydrates formed from bacterial decomposition in anaerobic environments, but some resulted from thermogenic formation deeper below the surface.

Economics determines how much will be extracted

As we develop more powerful technologies for locating and extracting fossil fuels, the proportions of these fuels that are physically accessible to us—the *technically recoverable* portions—tend to increase. However, whereas technology determines how much fuel *can* be extracted, economics determines how much *will* be extracted. This is because extraction becomes increasingly expensive as a resource is removed,

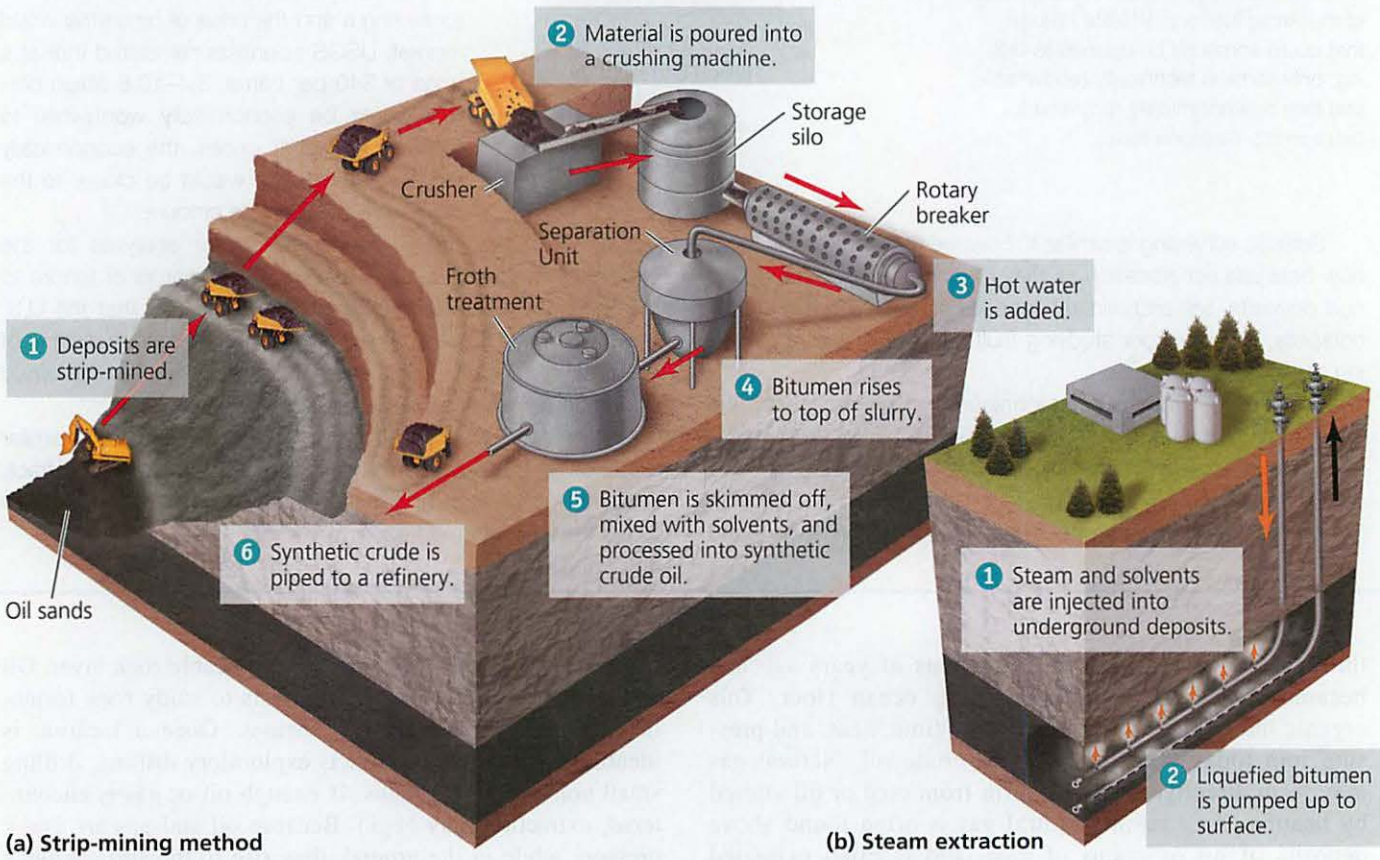


FIGURE 19.8 Oil sands are extracted by two processes. Near-surface deposits of oil sands **(a)** are strip-mined. Deeper deposits of oil sands **(b)** are liquefied and extracted through well shafts.

so companies rarely find it profitable to extract the entire amount. Instead, a company will consider the costs of extraction (and other expenses), and balance these against the income it expects from sale of the fuel. Because market prices of fuel fluctuate, the portion of fuel from a given deposit that is *economically recoverable* fluctuates as well. As market prices rise, economically recoverable amounts approach technically recoverable amounts.

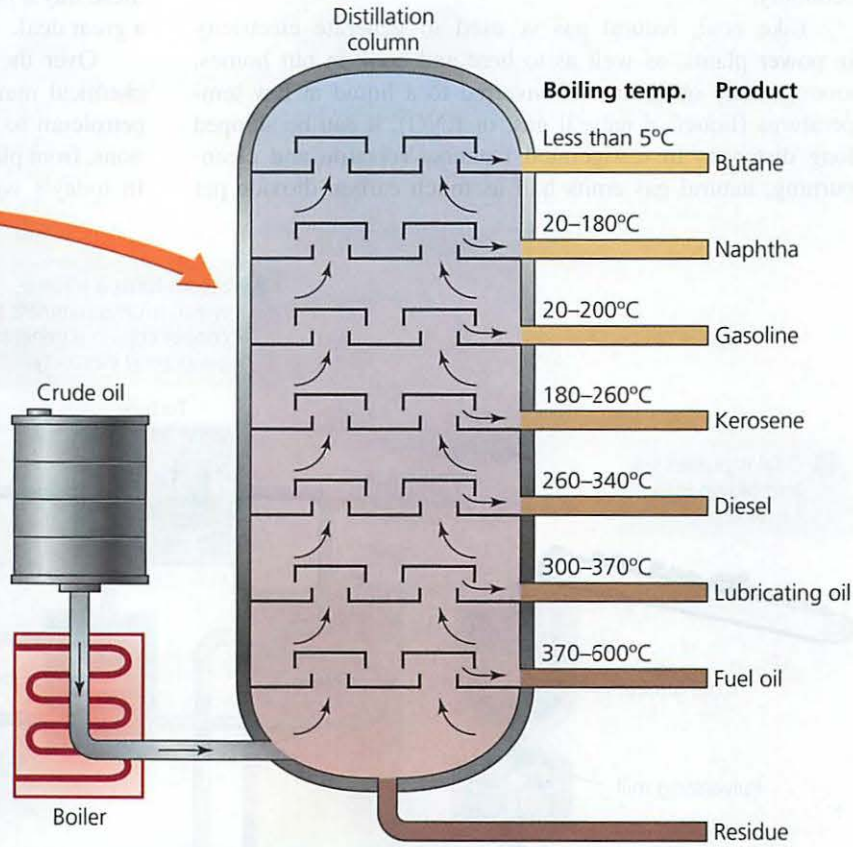
The amount of a fossil fuel that is technologically *and* economically feasible to remove under current conditions is termed its **proven recoverable reserve.** Proven recoverable reserves increase as extraction technology improves or as market prices of the fuel rise. Proven recoverable reserves decrease as fuel deposits are depleted by extraction or as market prices fall (making extraction unprofitable). Some examples of proven recoverable reserves are shown in Table 19.2 (p. 518).

Refining results in a diversity of fuels

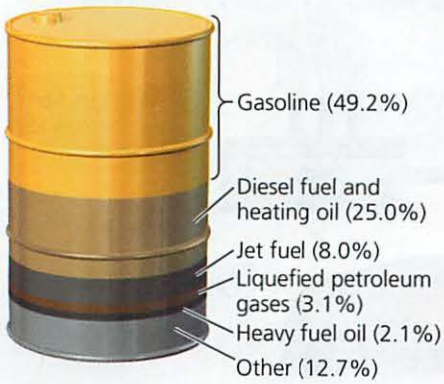
Once we extract oil or gas, it must be processed and refined before we can use it as an energy source (FIGURE 19.9). Because crude oil is a complex mix of hundreds of types of hydrocarbons, we can create many types of petroleum products by separating its various components. The many hydrocarbon molecules in crude oil have carbon chains of different lengths (p. 27). Chain length affects a substance's chemical properties, and this has consequences for human use, such as whether a given fuel burns cleanly in a car engine. Through the process of **refining** at a refinery, hydrocarbon molecules are separated by size and are chemically transformed to create specialized fuels for heating, cooking, and transportation, and to create lubricating oils, asphalts, and the precursors of plastics and other petrochemical products.



(a) Distillation columns



(b) Distillation process



(c) Typical output of refined oil

FIGURE 19.9 The refining process results in a range of petroleum products. At oil refineries **(a)**, crude oil is boiled, causing its many hydrocarbon constituents to volatilize and proceed upward **(b)** through a distillation column. Constituents that boil at the hottest temperatures and condense readily once the temperature cools will condense at low levels in the column. Constituents that volatilize at cooler temperatures will continue rising through the column and condense at higher levels, where temperatures are cooler. In this way, heavy oils (generally those with hydrocarbon molecules with long carbon chains) are separated from lighter oils (generally those with short-chain hydrocarbon molecules). Shown in **(c)** are percentages of each major category of product typically generated from a barrel of crude oil. *Data (c) from U.S. Energy Information Administration.*

Fossil fuels have many uses

The amounts of a fossil fuel that a nation extracts, and the amounts of a fossil fuel that a nation consumes, each depend on many factors. **TABLE 19.3** shows amounts extracted and amounts consumed (as percentages of global extraction and consumption) by leading nations.

Each major type of fossil fuel has its own mix of uses. People have burned coal to cook food, heat homes, and fire pottery for thousands of years and in many cultures across the globe. Coal-fired steam engines helped drive the industrial revolution by powering factories, agriculture, trains, and ships, and coal fueled the furnaces of the steel industry. Today we burn coal largely to generate electricity. In coal-fired power plants, coal combustion converts water to steam, which turns turbines to create electricity (**FIGURE 19.10**). Coal provides 40% of the electrical generating capacity of the United States, and it has powered the rise of China's surging economy.

Like coal, natural gas is used to generate electricity in power plants, as well as to heat and cook in our homes, among many other uses. Converted to a liquid at low temperatures (liquefied natural gas, or LNG), it can be shipped long distances in refrigerated tankers. Versatile and clean-burning, natural gas emits half as much carbon dioxide per unit of energy released as coal and two-thirds as much as oil. For this reason, many energy experts have proposed natural gas as a climate-friendly "bridge fuel" that can help us transition from today's polluting fossil fuel economy toward a clean renewable energy economy. However, many other experts worry that investing in natural gas will simply delay our transition to renewables and instead deepen our reliance on fossil fuels.

The modern use of oil for energy began after the 1850s, when crude oil gushed from the world's first commercial oil wells drilled in Ontario and Pennsylvania. Over the next 40 years, drillers in Pennsylvania supplied half the world's oil and helped establish a fossil-fuel-based economy that would hold sway for decades to come. Today our global society extracts and consumes nearly 200 gallons of oil each year for every man, woman, and child. Most is used as fuel for vehicles, including gasoline for cars, diesel for trucks, and jet fuel for airplanes. Fewer homes burn oil for heating these days, but industry and manufacturing continue to use a great deal.

Over the past several decades, refining techniques and chemical manufacturing have greatly expanded our uses of petroleum to include a wide array of products and applications, from plastics to lubricants to fabrics to pharmaceuticals. In today's world, petroleum-based products are all around

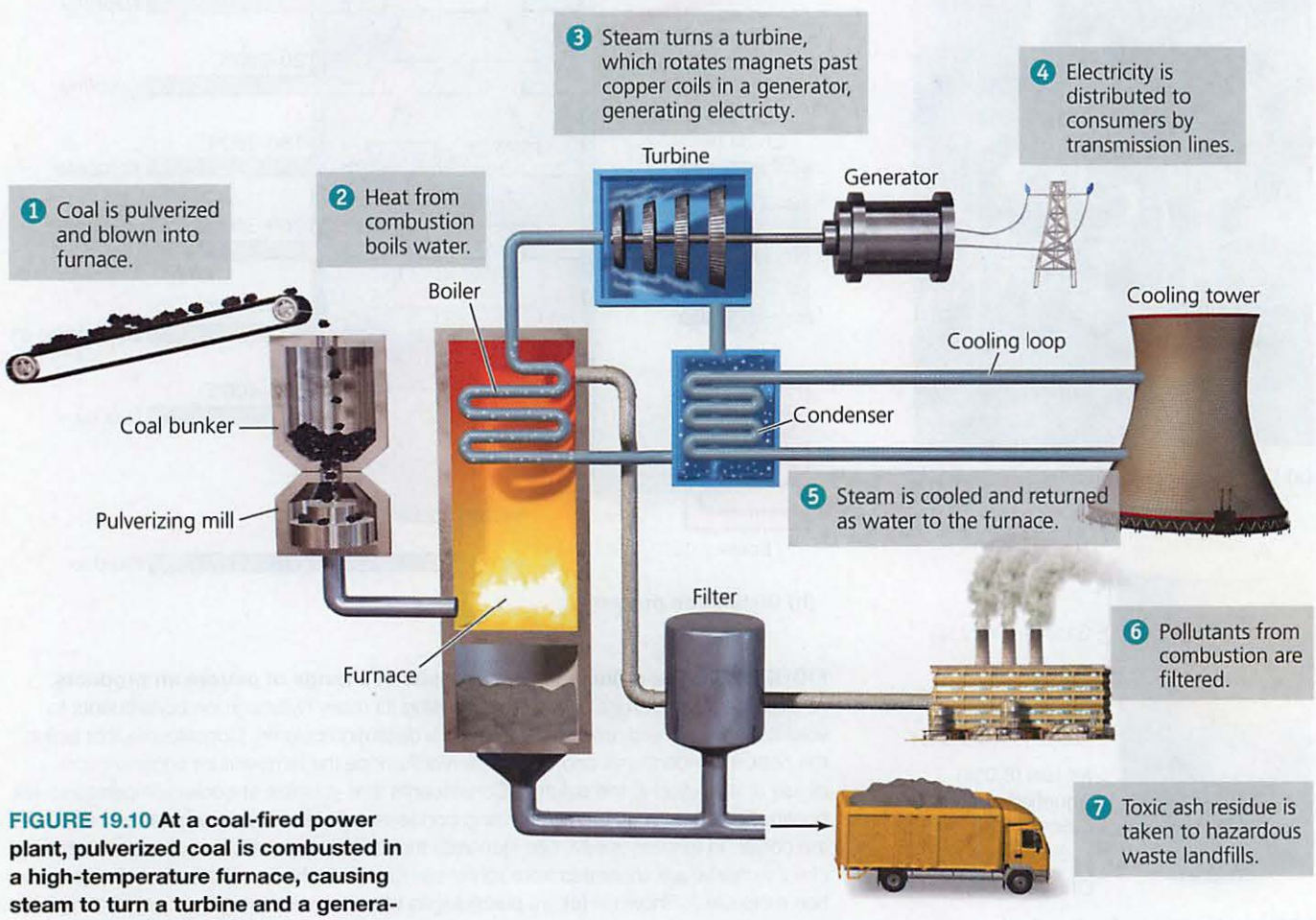


FIGURE 19.10 At a coal-fired power plant, pulverized coal is combusted in a high-temperature furnace, causing steam to turn a turbine and a generator to generate electricity.

TABLE 19.3 Top Extractors and Consumers of Fossil Fuels

EXTRACTION (% world extraction)		CONSUMPTION (% world consumption)	
COAL			
China	47.7	China	50.0
United States	11.9	India	10.6
India	7.4	United States	10.3
Australia	7.2	Japan	3.1
OIL			
United States	13.0	United States	19.7
Saudi Arabia	13.0	China	12.9
Russia	12.4	India	4.5
Canada	4.9	Japan	4.4
NATURAL GAS			
United States	22.0	United States	22.8
Russia	16.1	Russia	11.2
Iran	5.4	China	5.7
Qatar	5.1	Iran	5.5

Data from BP p.l.c., 2016. *Statistical review of world energy 2016.*

us in our everyday lives (FIGURE 19.11). Take a moment to explore Figure 19.11, and reflect on all the conveniences in your own life that result from petroleum products. The fact that petroleum is used to create so many items and materials we have come to rely on makes it vital that we take care to conserve our remaining oil reserves.

We are depleting fossil fuel reserves

Because fossil fuels are nonrenewable, the total amount available on Earth declines as we use them. Many scientists and oil industry analysts calculate that we have already extracted nearly half the world's conventional oil reserves. So far we have used up about 1.2 trillion barrels of oil, and most estimates hold that about 1.2 trillion barrels of proven reserves remain. Adding proven reserves of oil from oil sands in Canada and Venezuela brings the estimated total remaining to about 1.7 trillion barrels.

To assess how long this remaining oil will last, analysts calculate the **reserves-to-production ratio,** or R/P ratio, by dividing the amount of total remaining reserves by the annual rate of "production" (extraction and processing). At current levels of production (32 billion barrels globally per year), 1.7 trillion barrels would last about 53 more years. Applying the R/P ratio to natural gas, we find that the world's proven reserves of this resource would last 54 more years. For coal, the latest R/P ratio estimate is 110 years.

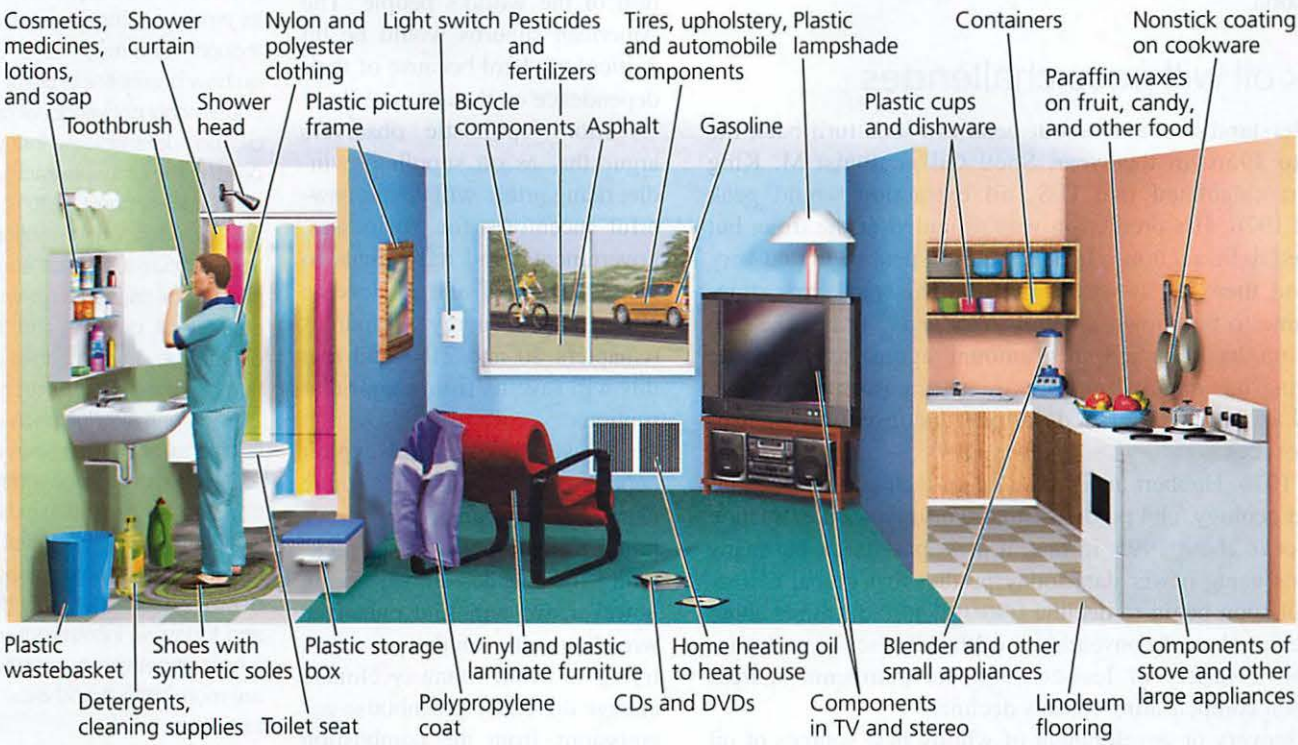


FIGURE 19.11 Petroleum products are everywhere in our daily lives. Petroleum is used to make many of the fabrics we wear, the materials we consume, and the plastics in countless items we use every day.

The actual number of years remaining for these fuels could turn out to be less than these figures suggest if our demand and production continue to increase. Alternatively, the actual number of years may end up being *more* than these figures suggest if we reduce demand and consumption by enhancing efficiency. The actual number of years may also turn out to be greater because proven recoverable reserves increase as new deposits are discovered, as extraction technology becomes more powerful, and as market prices rise.

For instance, hydraulic fracturing for natural gas in the Marcellus Shale and elsewhere in the United States has expanded the nation's proven reserves of natural gas considerably in recent years (Chapter 7). Likewise, hydraulic fracturing of the Bakken Formation—layers of shale and dolomite that underlie parts of North Dakota, Montana, and Canada—is allowing us to extract oil trapped tightly in this rock. By accessing this so-called *tight oil*, conventional oil held tightly in or near shale (which differs from shale oil, a petroleum liquid from specially processed oil shale), the United States has boosted its proven recoverable reserves of oil. In fact, the recent oil boom in North Dakota, along with increases in drilling deep offshore, enabled the United States, as of 2014, to become the world's largest extractor of oil.

Eventually, however, extraction of any nonrenewable resource will come to a peak and then decline. In general, extraction tends to decline once reserves are depleted halfway. If demand for the resource holds steady or rises while extraction declines, a shortage will result. With oil, this scenario has come to be nicknamed **peak oil.** Because we have already used roughly half of Earth's conventional oil reserves, many experts calculate that a peak oil crisis could begin soon.

Peak oil will pose challenges

To understand concerns about peak oil, let's turn back the clock to 1956. In that year, Shell Oil geologist M. King Hubbert calculated that U.S. oil extraction would peak around 1970. His prediction was ridiculed at the time, but it proved to be accurate; U.S. extraction peaked in that very year and then fell (FIGURE 19.12a). This peak in extraction came to be known as *Hubbert's peak*. Today U.S. oil extraction has reached this amount again, as hydraulic fracturing has enabled us to extract formerly inaccessible oil and as we have pursued various unconventional petroleum sources.

In 1974, Hubbert analyzed data on technology, economics, and geology, and predicted that worldwide oil extraction would peak about 1995. In fact, it grew past 1995, but many scientists using newer data today predict that global extraction will soon begin to decline (FIGURE 19.12b). Since about 2005, extraction of conventional oil has in fact been declining, and a variety of less-conventional petroleum sources have been compensating for this decline.

Discovery or development of wholly new sources of oil can delay the peak by boosting our overall proven reserves. This is what is happening as we exploit Canada's oil sands. People who count on a series of new sources becoming available in the future tend to believe we can continue relying on oil for a long time. Indeed, R/P ratios for oil have risen over recent decades. However, at some point we will reach peak oil—as well as "peak gas" and "peak coal." The question is when—and whether we will be prepared to deal with the resulting challenges.

Predicting an exact date for peak oil is difficult because many companies and governments do not reveal their true data on oil reserves. Moreover, estimates differ about how much oil we can continue extracting from existing deposits. For these reasons, estimates vary for the timing of an oil extraction peak, but most studies predict dates before 2035.

Whenever an oil peak occurs, if demand for oil continues to rise as supply falls, the divergence of demand and supply would drive up oil prices dramatically, triggering major economic ripple effects that could profoundly affect our lives. Writer James Howard Kunstler has sketched a frightening scenario of a post-peak world during what he calls "the long emergency": Lacking cheap oil with which to transport goods long distances, today's globalized economy would collapse into isolated local economies. Large cities would need to run urban farms to feed their residents, and with less mechanized farming and fewer petroleum-based fertilizers and pesticides, we might feed only a fraction of the world's people. The American suburbs would be hit particularly hard because of their dependence on the automobile.

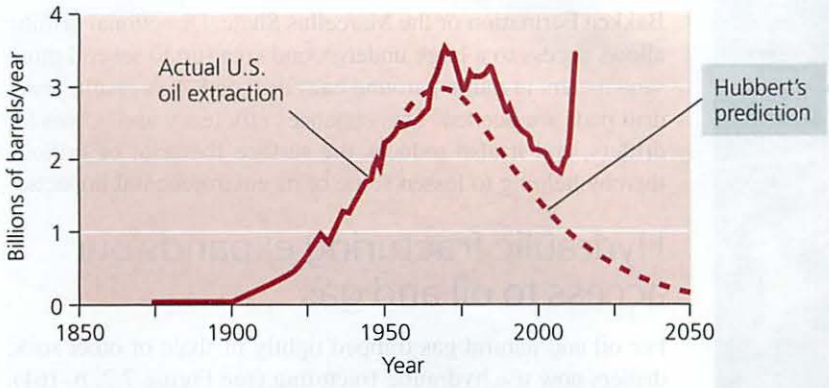
More optimistic observers argue that as oil supplies dwindle, rising prices will create powerful incentives for businesses, governments, and individuals to conserve energy and to develop alternative energy sources (Chapters 20 and 21)—and that this will save us from major disruptions.

If we discover and exploit enough new deposits to continue extracting more and more oil, we might postpone our day of reckoning for decades. If we do so, however, we will find ourselves wrestling with another concern: trying to avoid runaway climate change driven by greenhouse gas emissions from the combustion of all that additional oil!

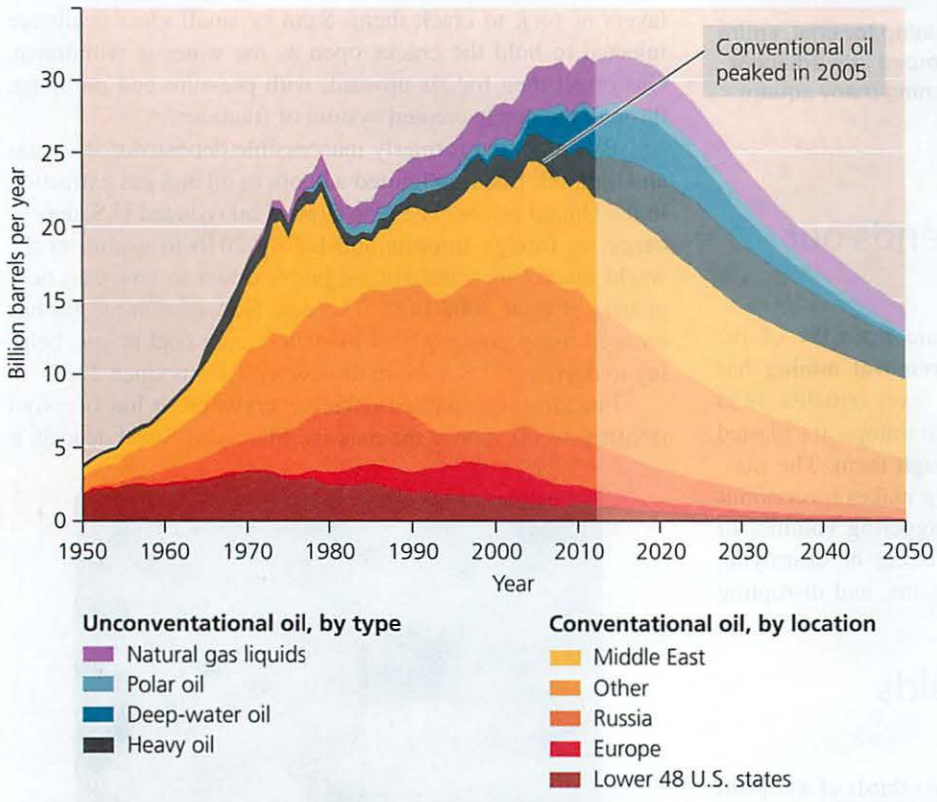
FAQ

Hasn't "peak oil" been debunked? We're extracting more oil all the time, right?

An eventual peak is inevitable with any nonrenewable resource, so the notion of peak oil is sound. Its timing is a major question, though—and much depends on how one defines "oil." If one counts only conventional crude oil, then data indicate that we passed the global extraction peak back around 2005. If one also includes "unconventional" oil from difficult-to-access sources such as oil sands, deep-water offshore oil, polar oil, and "tight oil" freed by fracking, then extraction has been roughly flat since 2005. If one also lumps in various additional petroleum sources as "oil" (such as liquids condensed from natural gas), then extraction is still rising. In the big picture, conventional oil has already been declining for more than a decade, and today we increasingly rely on a host of petroleum sources that are more difficult and expensive to access.



(a) Hubbert's prediction of peak in U.S. oil extraction, together with actual data



(b) Modern prediction of peak in global oil extraction

FIGURE 19.12 Peak oil describes a peak in extraction. U.S. oil extraction peaked in 1970 **(a)**, just as geologist M. King Hubbert had predicted. Drilling in Alaska and the Gulf of Mexico enhanced extraction during the subsequent decline, and today extraction has risen sharply as deep offshore drilling and hydraulic fracturing have made new deposits accessible. As for global oil extraction, many analysts calculate that it may soon peak. Shown in **(b)** is one projection, from a recent analysis by scientists at the Association for the Study of Peak Oil. This study showed that conventional sources of oil peaked around 2005, and since then unconventional sources have driven the continued overall rise. Paler shades of color indicate future data predicted by the researchers. *Data from* ***(a)*** *Hubbert, M.K., 1956.* Nuclear energy and the fossil fuels. *Shell Development Co. Publ. No. 95, Houston, TX; and U.S. Energy Information Administration; and* ***(b)*** *Campbell, C.J., and Association for the Study of Peak Oil. By permission of Dr. Colin Campbell.*

Reaching Further for Fossil Fuels

To stave off the day when supplies of oil, gas, and coal begin to decline, we are investing more and more money, energy, and technology into locating and extracting new fossil fuel deposits. We are extending our reach for fossil fuels in several ways:

- Mountaintop mining for coal
- Secondary extraction from existing wells
- Directional drilling
- Hydraulic fracturing for oil and gas
- Offshore drilling in deep waters
- Moving into ice-free waters of the Arctic
- Exploiting new "unconventional" fossil fuel sources

All these pursuits are expanding the amount of fossil fuel energy available to us. As we extend our mining and drilling efforts into less-accessible places to obtain fuel that is more difficult and more expensive to extract, we expand our proven reserves. However, we also reduce the EROI ratios of our fuels, intensify pollution, and worsen climate change. At a time when many people feel we should be transitioning to clean and renewable energy, our society instead appears to be doubling down on its bet on fossil fuels.



FIGURE 19.13 In mountaintop removal mining for coal, entire mountain peaks are leveled and fill is dumped into adjacent valleys, as shown in this aerial view spanning many square miles in West Virginia.

Mountaintop mining extends our reach for coal

Coal mining has long been an economic mainstay of the Appalachian region, but **mountaintop removal mining** has brought coal extraction to a whole new level (FIGURE 19.13 and p. 639). In this method, entire mountaintops are blasted away to access coal seams running through them. The massive scale of mountaintop removal mining makes it economically efficient. However, it can cause staggering volumes of rock and soil to slide downslope, degrading or destroying entire hillsides, polluting or burying streams, and disrupting life for people living nearby.

Secondary extraction yields additional fuel

At a typical oil or gas well, as much as two-thirds of a deposit may remain in the ground after primary extraction, the initial drilling and pumping of oil or gas. So, companies may return and conduct secondary extraction using new technology or approaches to force the remaining oil or gas out by pressure. In secondary extraction for oil, solvents are injected, underground rocks are flushed with water or steam, or hydraulic fracturing is used. Because secondary extraction is more expensive than primary extraction, most deposits undergo secondary extraction only when market prices of oil and gas are high enough to make the process profitable.

Directional drilling reaches more fuel with less impact

Engineers have brought us a long way from the days when we simply sank a vertical shaft into the ground to suck up oil and gas. Today's **directional drilling** technology allows drillers to bore down vertically and then curve to drill horizontally. This enables them to follow horizontal layered deposits such as the Bakken Formation or the Marcellus Shale. Directional drilling allows access to a large underground area (up to several thousand meters in radius) around each drill pad. As a result, fewer drill pads are needed. This enhances efficiency and profits for drillers, and it also reduces the surface footprint of drilling, thereby helping to lessen some of its environmental impacts.

Hydraulic fracturing expands our access to oil and gas

For oil and natural gas trapped tightly in shale or other rock, drillers now use hydraulic fracturing (see Figure 7.2, p. 161). **Hydraulic fracturing** (also called **fracking**) involves pumping chemically treated water under high pressure into deep layers of rock to crack them. Sand or small glass beads are injected to hold the cracks open as the water is withdrawn. Gas or oil then travels upward, with pressure and pumping, through the newly created system of fractures.

By unlocking formerly inaccessible deposits of shale gas and tight oil, fracking ignited a boom in oil and gas extraction in the United States. The new flow of oil reduced U.S. dependence on foreign imports and led by 2016 to a glut on the world market that brought oil prices down to less than one-quarter of their 2008 high. The new flow of natural gas has enabled many power plants to switch from coal to gas, helping to decrease U.S. carbon dioxide emissions since 2007.

Fracking has sparked debate everywhere it has occurred (FIGURE 19.14). Above the massive Marcellus Shale deposit, it

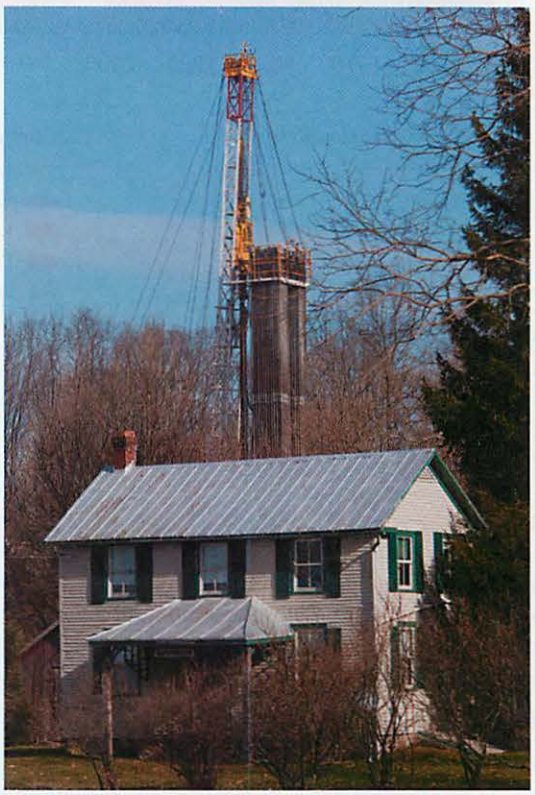


FIGURE 19.14 Hydraulic fracturing is expanding U.S. extraction of oil and natural gas, but is also sparking debates in communities where it takes place. This drill rig is fracking for shale gas on private land near homes in rural Pennsylvania.

is affecting the landscapes, economies, politics, and everyday lives of people in Pennsylvania, Ohio, New York, and neighboring states (see Chapter 7). The choices people face between financial gain and protecting their health, drinking water, and environment have been dramatized in popular films such as *Promised Land* and *Gasland*. Recently in North Dakota, fracking for oil supercharged the economy and drew young people from around the nation for high-paying jobs, but it also polluted the landscape, drew down water resources, and left many workers jobless once oil prices fell and rigs shut down.

We are drilling farther offshore

Roughly 35% of the oil and 10% of the natural gas extracted in the United States today come from offshore sites, primarily in the Gulf of Mexico and secondarily off southern California. The Gulf today is home to 90 drilling rigs and 3500 production platforms—each of them an engineering marvel built to withstand wind, waves, and ocean currents. Geologists estimate that most U.S. gas and oil remaining occurs offshore and that deep-water sites in the Gulf of Mexico alone may hold 59 billion barrels of oil.

We have been drilling in shallow water for several decades, but as oil and gas are depleted at shallow-water sites and as drilling technology improves, the industry is moving into deeper and deeper water. This poses risks, however, and our ability to drill in deep water has outpaced our capacity to deal with accidents. In the *Deepwater Horizon* oil spill of 2010 (pp. 429, 534–537), faulty equipment allowed natural gas accompanying an oil deposit to shoot up a well shaft. The gas ignited atop the platform, killing 11 workers and leading to the largest accidental oil spill in history. The fact that it took 86 days for the company that owned the platform, British Petroleum, to plug its leak demonstrates the challenge of addressing an emergency situation a mile or more beneath the surface of the sea. BP's Macondo well, where the accident took place, lay beneath 1500 m (5000 ft) of water. The deepest wells in the Gulf of Mexico are now twice that depth.

In 2008, responding to rising gasoline prices and seeking to lessen dependence on foreign oil, the U.S. Congress lifted a long-standing moratorium on offshore drilling along much of the nation's coastline. The Obama administration in 2010 followed through by designating vast areas open for drilling. These included most waters along the Atlantic coast from Delaware south to central Florida, a region of the eastern Gulf of Mexico, and most waters off Alaska's North Slope. However, just weeks after this announcement, the *Deepwater Horizon* spill occurred. Public reaction forced the Obama administration to backtrack, canceling offshore drilling projects it had approved and putting a hold on further approvals until new safety measures could be devised. In 2011, after weighing economic and environmental concerns, the administration issued a five-year plan that opened access to 75% of technically recoverable offshore oil and gas reserves while banning drilling offshore from states that did not want it. Drilling leases were expanded off Alaska and in the Gulf of Mexico, but areas along the East and West Coasts were not opened to drilling.

Melting ice is opening the Arctic

Today all eyes are on the Arctic. As global climate change melts the sea ice that covers the Arctic Ocean (pp. 494, 501), new shipping lanes are opening and nations and companies are jockeying for position, scrambling to lay claim to areas of ocean where fossil fuels might lie beneath the seafloor. Offshore drilling in Arctic waters, however, poses severe pollution and safety risks. Frigid temperatures, ice floes, winds, waves, and brutal storms make conditions challenging and accidents likely. If a spill were to occur, icebergs, pack ice, storms, cold, and wintertime darkness would hamper response efforts, while frigid water temperatures would slow the natural breakdown of oil.

So far, Royal Dutch Shell has been the only company to pursue offshore drilling in Alaskan waters—and it has met with one mishap after another. In 2012–2013 its *Kulluk* drilling rig ran aground while being towed south from Alaska during a storm. Another drilling ship nearly met the same fate in the Aleutian Islands, and the containment dome intended to control potential leaks was crushed during testing. Then in 2015 one of Shell's icebreakers, the *Fennica*, ran aground and had to be towed all the way to Portland, Oregon, for repairs. On its way out of the harbor, protesters rowing in kayaks and dangling daringly from a bridge blocked its path, gaining media attention for their cause. This followed protests in Seattle two months earlier over Shell's plans to house drilling rigs in Seattle's port (**FIGURE 19.15**). Meanwhile, Arctic storms halted Shell's drilling. That fall Shell gave up and withdrew from the Arctic after spending $7 billion in efforts to drill there.

We are exploiting new fossil fuel sources

Three sources of "unconventional" fossil fuels—oil sands, oil shale, and methane hydrate—are abundant, and together could theoretically supply our civilization for centuries. The oil sands



FIGURE 19.15 "Kayaktivists" in Seattle protested Shell's plans to drill for oil in the Arctic Ocean by blockading a drilling rig in 2015.

of Alberta—and those in Venezuela, which hold even more oil—are already increasing the amount of oil available to us.

The world's known deposits of oil shale may contain 3 trillion barrels of oil (more than all the world's conventional crude oil), but most of this will not easily be extracted. About 40% of global reserves are in the United States, mostly on public land in Colorado, Wyoming, and Utah. Shale oil is costly to extract, and its EROI is very low, with estimates ranging from 4:1 down to just 1.1:1. Historically, oil prices have been too low to make processing shale oil profitable, but each time oil prices rise, shale oil again attracts attention.

As for methane hydrate, scientists estimate there are enormous amounts of this substance on Earth, holding perhaps twice as much carbon as all known deposits of oil, coal, and natural gas combined. However, we do not yet know whether their extraction is safe and reliable. Japan recently extracted methane hydrate from the seafloor by sending down a pipe and lowering pressure within it so that the methane turned to gas and rose to the surface. Yet if extraction were to destabilize a seafloor methane hydrate deposit, a sudden release of gas could cause a landslide and tsunami and emit large amounts of methane, a potent greenhouse gas, into the atmosphere.

Oil sands, oil shale, and methane hydrate are abundant, but they are no panacea for our energy challenges. Their net energy values and EROI ratios are very low, because they are expensive to extract and process. These fuels also exert severe environmental impacts on land and water. Moreover, burning them would likely emit more greenhouse gases than our use of coal, oil, and natural gas currently does, worsening air pollution and climate change.

Addressing Impacts of Fossil Fuel Use

Our society's love affair with fossil fuels and the many petrochemical products we develop from them has helped to ease constraints on travel, lengthen our life spans, and boost our material standard of living beyond what our ancestors could have dreamed. Yet continued reliance on fossil fuels poses growing risks to human health; environmental quality; and social, political, and economic stability. The predicted impacts from climate change alone are so great that the International Energy Agency's chief economist recently joined a growing chorus of scientists in concluding that we will need to leave most fossil fuels in the ground if we are to avoid dangerous climate disruption and preserve the planet that we know. Let's now briefly survey the main impacts of fossil fuel use—beginning with extraction, continuing through emissions, and ending with social issues—and assess ways to minimize these impacts.

Extraction of fossil fuels brings many environmental impacts

The means by which we remove fossil fuel resources from the earth have direct impacts on landscapes and natural habitats (FIGURE 19.16), as well as a diversity of other consequences for ecological processes and environmental quality.



FIGURE 19.16 Oil sands extraction dramatically alters Alberta's forested landscape. Shown is a portion of the Suncor mine near Fort McMurray.

Coal The mining of coal exerts substantial impacts on natural systems and human well-being (p. 635). Subsurface coal mining has long posed health and safety risks to miners. Miners are vulnerable to accidents, and they breathe coal dust and hazardous gases in confined spaces, which often leads to respiratory diseases. Strip mining, for its part, destroys large swaths of habitat and causes extensive soil erosion. It also can cause chemical runoff into waterways through acid mine drainage (p. 634), whereby sulfide minerals in freshly exposed rock surfaces react with oxygen and rainwater to produce sulfuric acid, which can leach toxic metals from rocks. Most developed nations require mining companies to restore affected areas after mining. This reclamation is beneficial, but rarely is able to recreate the ecological communities that preceded mining (p. 641).

Mountaintop removal mining (pp. 530, 639) exerts impacts that exceed even those of strip mining. When countless tons of rock and soil are removed from the top of a mountain, material slides downhill, where immense areas of habitat can be degraded or destroyed and creek beds can be clogged and polluted, affecting wildlife, ecosystems, and local residents. (We explore all these issues of coal mining in Chapter 23.)

Oil and natural gas To drill for conventional oil or gas on land, road networks must be constructed and many sites may be explored in the course of prospecting. The extensive infrastructure needed to support a full-scale drilling operation typically includes access roads, transport pipelines, housing for workers, waste piles for excavated soil, and ponds to collect toxic sludge. These tend to pollute the soil, air, and water; fragment habitats; and disturb wildlife. These impacts can be readily seen at most drilling sites, and have been particularly well documented on the Alaskan tundra, where policymakers continue to debate whether to open the Arctic National Wildlife Refuge to drilling.

Fortunately, directional drilling (p. 530) is becoming widely used today. This provides much greater reach than traditional vertical drilling, so fewer drill pads are needed and less infrastructure is required, reducing the footprint on the landscape.

Hydraulic fracturing Extracting oil or natural gas by hydraulic fracturing exerts all the impacts of conventional drilling, as well as posing additional concerns. In fracking, chemicals are mixed with pressurized water and sand, a combination that is injected deep underground, giving rise to risks of water pollution that are not yet completely understood. One risk is that fracking fluids may leak out of drilling shafts and into aquifers that people rely on for drinking water. Another concern is that methane may contaminate groundwater used for drinking if it travels up the fractures or leaks through the shaft (see **The Science behind the Story**, Chapter 7, pp. 164–165).

Hydraulic fracturing also gives rise to air pollution as methane and volatile toxic components of fracking fluids seep up from drilling locations. Some of the unhealthiest air in America was recently found in a remote region of Wyoming near fracking operations. Many residents of areas near fracking sites have experienced polluted air and fouled drinking water; more research is needed to assess the extent of such pollution and to quantify the health risks.

In addition, hydraulic fracturing consumes immense volumes of fresh water. Injected water often returns to the surface laced with salts, radioactive elements such as radium, and toxic chemicals such as benzene from deep underground. This wastewater may be sent to sewage treatment plants that are not designed to handle the contaminants and that do not test for radioactivity. In Pennsylvania, millions of gallons of drilling waste from Marcellus Shale fracking sites have been sent to treatment plants, which then release their water into rivers that supply drinking water for people in Pittsburgh, Harrisburg, and other cities. In response to public outcry and government pressure, the oil and gas industry is beginning to reduce its consumption of clean water by reusing its wastewater in multiple injections.

Finally, fracking is now known to cause earthquakes (see **The Science behind the Story**, Chapter 2, pp. 40–41). Most have been minor, but this does raise questions about whether all social and economic costs have been considered.

Oil sands Impacts from the extraction of oil sands surpass those of conventional fossil fuel extraction. Because everything is cleared across huge areas when oil sands are mined (see Figure 19.16), this results in large-scale loss of boreal forest (in Alberta) or tropical forest (in Venezuela). Deforestation has severe consequences for species, habitats, ecosystems, soil, water, climate, and people (Chapter 12). Industry representatives counter that the area deforested in Alberta so far amounts to just 0.1% of Canada's vast boreal forest. They also point out that they are mandated to attempt restoration afterward. However, effective reclamation has not yet been demonstrated, and regions denuded by the very first oil sand mine in Alberta more than 30 years ago have still not recovered.

Three barrels of water are required to extract each barrel of oil from oil sands, and the toxic wastewater that results is discharged into huge reservoirs. The Syncrude mine's tailings reservoir near Fort McMurray, Alberta, for example, is so massive that it is held back by the world's second-largest dam. Migratory waterfowl land on water bodies like these and are killed as the oily water gums up their feathers and impairs their ability to insulate themselves.

Fuels can leak during transport and storage

Once fossil fuels are extracted, they must be transported for processing and refining, then transported again to consumers. Between transport episodes they may be stored for long periods. At each stage, there is the risk of leakage.

Rail transport Once mined, coal is generally transported by rail in open cars, which releases coal dust into the air. In the Pacific Northwest, clean energy advocates are opposing the transport of coal by train from the interior West where it is mined to coastal terminals, to be shipped to Asia. Pollution along the route is one concern; another is that this facilitates China's reliance on coal, a driver of global climate change.

Oil is also transported by rail, in pressurized tank cars. In recent years, as oil extraction in North America has soared, it has surpassed pipeline capacity, and a great deal of oil is being transported by rail instead. Tragically, a series of explosive derailments of trains carrying corrosive North Dakota crude oil has illustrated the dangers of carrying oil by train (FIGURE 19.17). Worst was the 2013 explosion in Lac-Mégantic, Quebec, which killed 47 people and destroyed the town's center. In the two following years the United States saw 10 major explosions, and in 2014 there were 141 tanker spills. The Obama administration responded with regulations to upgrade the safety of tanker cars; industry complained of additional cost while safety advocates said the steps were not strong enough. Ironically, while rejection of the Keystone XL pipeline may have averted a number of environmental and social impacts, it is also contributing to the surge in oil transport by rail.



FIGURE 19.17 Explosive crashes of trains carrying oil, such as this one in Lac-Mégantic, Quebec, are rising, as North American oil extraction has surpassed pipeline capacity.

Methane leaks Any time natural gas leaks into the air, its main component, methane, is added to the atmosphere. Methane is a powerful greenhouse gas (p. 483), so its leakage worsens global warming and climate change. Methane can leak at various points during the extraction, transport, and processing of natural gas—and it can leak from aging pipes that bring natural gas to consumers. A 2015 study of the Boston region found that 2.7% of natural gas piped to homes and businesses was escaping into the air—higher than the 1% previously assumed. By comparison, researchers estimate that 3.6–7.9% of natural gas extracted by shale gas fracking operations leaks into the air.

A great deal of methane also escapes to the atmosphere from oil drilling sites where gas accompanying an oil deposit is released to the air because pipelines for the gas do not exist. At many such sites, natural gas is flared off—in other words, the stream of gas is set on fire. This produces carbon dioxide, however, which is also a greenhouse gas.

Pipeline spills Oil is commonly conveyed by pipeline, and pipelines are subject to corrosion, vandalism, and equipment malfunction, any of which can result in spills that contaminate soil and water. Oil from Canada's oil sands (which is more corrosive than conventional crude oil) has spilled from a number of pipelines, fouling the Kalamazoo River in Michigan; a residential neighborhood of Mayflower, Arkansas; and other areas. People living along the initial proposed route of the Keystone XL pipeline worried that if oil were to spill from that pipeline, it would sink into the area's porous ground and quickly reach the region's shallow water table, contaminating the Ogallala Aquifer. This aquifer (p. 388) provides 2 million Americans with drinking water and irrigates a large portion of U.S. agriculture.

Marine oil spills Of the many ways in which fossil fuels pollute water, what comes to mind first for most people is how oil spilled from tanker ships or drilling platforms can foul coastal waters and beaches. In 2010, BP's *Deepwater Horizon* offshore drilling platform exploded and sank off the coast of Louisiana (FIGURE 19.18). Eleven workers were killed, and oil gushed out of a broken pipe on the ocean floor a mile beneath the surface at a rate of 30 gallons per second. Emergency shut-off systems failed, and BP engineers tried one solution after another; but as discussed earlier, the flow of oil and gas continued out of control for three months, spilling roughly 4.9 million barrels (206 million gallons) of oil. The crisis proved difficult to control because people had never had to deal with a spill so deep underwater. It revealed that offshore drilling presents serious risks of environmental impact that may be difficult to address.



FIGURE 19.18 The explosion at BP's *Deepwater Horizon* drilling platform in 2010 unleashed the world's largest accidental oil spill. Here vessels try to put out the blaze.

As the oil spread through the Gulf of Mexico and washed ashore, the region suffered a wide array of impacts (FIGURE 19.19). Of the countless animals killed, most conspicuous were birds, which cannot regulate their body temperature once their feathers become coated with oil. However,



(a) Brown pelican coated in oil



(b) Beach cleanup

FIGURE 19.19 Impacts of the *Deepwater Horizon* spill were many. This brown pelican, coated in oil **(a)**, was one of countless animals killed. For months, volunteers and workers labored **(b)** to clean oil from the Gulf's beaches.

the underwater nature of the BP spill meant that unknown numbers of fish, shrimp, corals, and other marine animals also were killed, affecting ecosystems in complex ways. Plants in coastal marshes died, and the resulting erosion put New Orleans and other coastal cities at greater risk from storm surges and flooding. Gulf Coast fisheries, which supply much of the nation's seafood, were hit hard, with thousands of fishermen and shrimpers put out of work. Beach tourism suffered, and indirect economic and social impacts have lasted for years. Throughout this process, scientists have been studying aspects of the spill and its impacts on the region's people and natural systems (see **THE SCIENCE BEHIND THE STORY**, pp. 536–537).

The *Deepwater Horizon* spill was the largest accidental oil spill in world history, far eclipsing the spill from the *Exxon Valdez* tanker in 1989. In that event, oil from Alaska's North Slope, piped to the port of Valdez through the trans-Alaska pipeline, caused long-term damage to ecosystems and economies in Alaska's Prince William Sound after the tanker ran aground. Nearly 30 years later, a layer of oil remains in the sand of the region's beaches.

The *Exxon Valdez* event led U.S. policymakers to tighten regulation and improve spill-response capacity. However, if drilling moves into Arctic waters, our capacity to control accidents could be sorely tested by the harsh conditions. In U.S. Arctic waters open to oil and gas leasing, some sites are 1000 miles from the nearest Coast Guard station.

Fortunately, pollution from large spills has declined in recent decades (see Figure 16.16, p. 432), thanks to government regulations (such as requiring double-hulled ships) and improved spill-response efforts. And although large catastrophic oil spills have significant impacts on the marine environment, most water pollution from oil results from countless small non-point sources (see Figure 15.23, p. 406). Oil from automobiles, homes, industries, gas stations, and businesses runs off roadways and enters rivers and wastewater facilities, eventually being discharged into the ocean. Water pollution from industrial point sources has been greatly reduced in the United States following the Clean Water Act (Chapter 15), and many solutions exist to address non-point-source pollution.

Carbon emissions drive climate change

When we burn fossil fuels, we alter fluxes in Earth's carbon cycle (p. 120). We essentially remove carbon from a long-term reservoir underground and release it into the air. This occurs as carbon from the hydrocarbon molecules of fossil fuels unites with oxygen from the atmosphere during combustion, producing carbon dioxide (CO_2). Carbon dioxide is a greenhouse gas (p. 482), and CO_2 released from fossil fuel combustion warms our planet and drives changes in global climate (Chapter 18).

Because global climate change is beginning to have diverse, severe, and widespread ecological and socioeconomic impacts, carbon dioxide pollution (**FIGURE 19.20**) is becoming recognized as the single biggest negative consequence of fossil fuel use. Methane is also a potent greenhouse gas that drives climate warming. Switching to new fossil fuel sources may only make emissions worse; oil sands are estimated to generate 14–20% more greenhouse gas emissions than conventional oil, and shale oil is still more polluting.

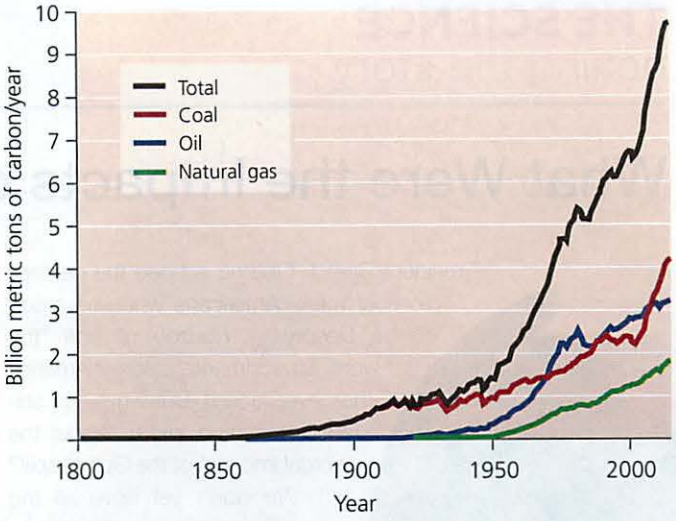


FIGURE 19.20 Emissions from fossil fuel combustion have risen dramatically as nations have industrialized and as population and consumption have grown. Here, global emissions of carbon from carbon dioxide are subdivided by source (coal, oil, or natural gas). *Data from Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, TN.*

DATA By what percentage have carbon emissions risen since the year your mother or father was born?

Go to **Interpreting Graphs & Data** on MasteringEnvironmentalScience®

Fossil fuel emissions also pose health risks

Besides modifying our climate, fossil fuel emissions affect human health. Combusting coal may emit mercury that can bioaccumulate in organisms' tissues, poisoning animals as it moves up food chains (p. 368) and posing health risks to people. Gasoline combustion in automobiles releases pollutants that irritate the nose, throat, and lungs, as well as cancer-causing hydrocarbons such as benzene and toluene. Gases such as hydrogen sulfide can evaporate from crude oil, irritate the eyes and throat, and cause asphyxiation. Crude oil also may contain trace amounts of poisons such as lead and arsenic. As a result, workers at drilling operations, at refineries, and in other jobs that entail frequent exposure to oil can develop serious health problems, including cancer.

The combustion of oil in vehicles and coal in power plants releases sulfur dioxide and nitrogen oxides, which contribute to smog (pp. 459–464) and acid deposition (p. 469). Air pollution from fossil fuel combustion is intensifying in developing nations that are industrializing, but it has been reduced in developed nations as a result of laws such as the U.S. Clean Air Act and government regulations to protect public health (Chapter 17). In these nations, public policy

What Were the Impacts of the Gulf Oil Spill?



A scientist rescues an oiled Kemp's ridley sea turtle.

President Barack Obama echoed the perceptions of many Americans when he called the *Deepwater Horizon* oil spill "the worst environmental disaster America has ever faced." But what has scientific research told us about the actual impacts of the Gulf oil spill?

We don't yet have all the answers, because the deep waters affected by the spill have been difficult for scientists to study. A great deal will remain unknown. Yet the intense and focused scientific response to the spill demonstrates the dynamic way in which science can assist society.

As the spill was taking place, government agencies called on scientists to help determine how much oil was leaking. Researchers eventually determined the rate reached 62,000 barrels per day. Using underwater imaging, aerial surveys, and shipboard water samples, researchers tracked the movement of oil up through the water column and across the Gulf. These data helped predict when and where oil might reach shore, thereby serving to direct prevention and cleanup efforts.

Meanwhile, as engineers struggled to seal off the well using remotely operated submersibles, researchers assisted government agencies in assessing the fate of the oil (**FIGURE 1**). These data would help inform studies of the oil's impacts on marine life and human communities.

Tracking movement of the oil underwater was challenging. University of Georgia biochemist Mandy Joye, who had studied natural seeps in the Gulf for years, documented that the leaking wellhead was creating a plume of oil the size of Manhattan. She also found evidence of low oxygen concentrations, or hypoxia (p. 104), because some bacteria consume oil and gas, depleting oxygen from the water and making it uninhabitable for fish and other creatures.

Joye and other researchers feared that the thinly dispersed oil might prove devastating to plankton (the base of the marine food chain) and to the tiny larvae of shrimp, fish, and oysters (the pillars of the fishing industry). Scientists taking water samples documented sharp drops in plankton during the spill, but it will take years to learn whether the impact on larvae will diminish populations of adult fish and shellfish. Studies on the condition of living fish in the region show gill damage, tail rot, lesions, and reproductive problems at much higher levels than is typical.

What was happening to life on the seafloor was a mystery, because only a handful of submersible vehicles in the world are able to travel to the crushing pressures of the deep sea. Luckily, a team of researchers led by Charles Fisher of Penn State University was scheduled to embark on a regular survey of deep-water coral across the Gulf of Mexico in late 2010. Using the three-person submersible *Alvin* and the robotic vehicles *Jason* and *Sentry*, the team found healthy coral communities at sites far away from the Macondo well but found dying corals and brittlestars covered in a brown material at a site 11 km from the Macondo well.

Eager to determine whether this community was contaminated by the BP oil spill, the research team added chemist Helen White of Haverford College and returned a month later, thanks to a National Science Foundation program that

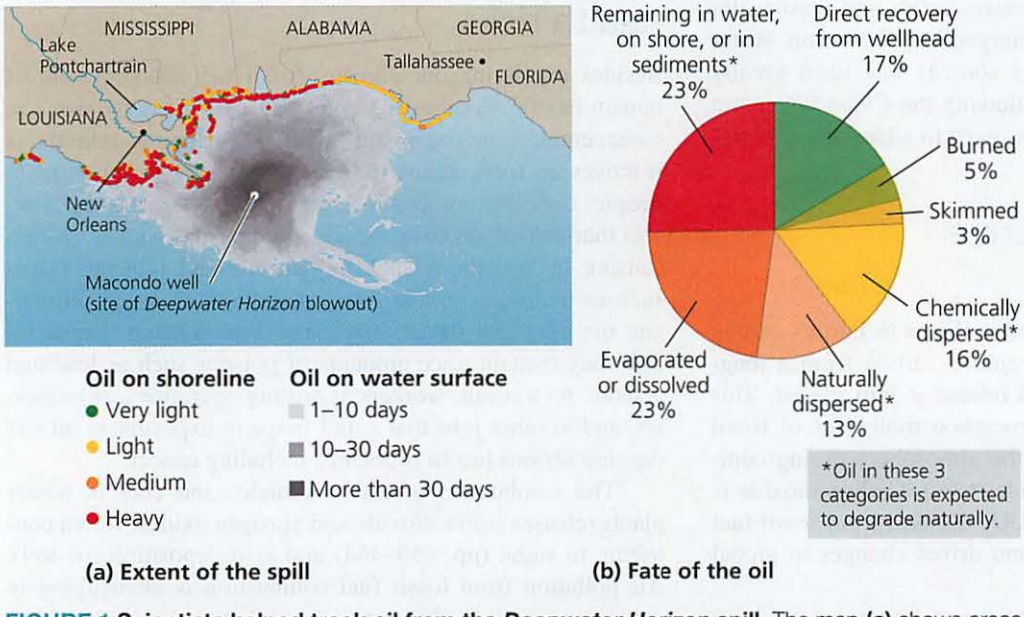


FIGURE 1 Scientists helped track oil from the *Deepwater Horizon* spill. The map **(a)** shows areas polluted by oil. The pie chart **(b)** gives a breakdown of the oil's fate. *Source: (a) NOAA Office of Response and Restoration; (b) NOAA.*

funds rapid response research. On this trip, chemical analysis of the brown material showed it to match oil from the BP spill.

Other questions revolve around impacts of the chemical dispersant that BP used to break up the oil, a compound called Corexit 9500. Work by biologist Philippe Bodin following the *Amoco Cadiz* oil spill in France in 1978 had found that Corexit 9500 appeared more toxic to marine life than the oil itself. BP threw an unprecedented amount of this chemical at the *Deepwater Horizon* spill, injecting a great deal directly into the path of the oil at the wellhead. This caused the oil to dissociate into trillions of tiny droplets that dispersed across large regions. Many scientists worried that this expanded the oil's reach, affecting more plankton, larvae, and fish.

Impacts of the oil on birds, sea turtles, and marine mammals were less difficult to assess, and hundreds of these animals were cleaned and saved by wildlife rescue teams. Officially confirmed deaths numbered 6104 birds, 605 turtles, and 97 mammals, but a much larger, unknown, number surely succumbed to the oil and were never found. What impacts this mortality may have on populations in coming years is unclear. (After the *Exxon Valdez* spill in Alaska in 1989, populations of some species rebounded, but populations of others have never come back.) Researchers are following the movements of marine animals in the Gulf with radio transmitters to try to learn what effects the oil may have had.

As images of oil-coated marshes saturated the media, researchers worried that widespread death of marsh grass would leave the shoreline vulnerable to severe erosion by waves. Fortunately, researchers found that oil did not penetrate to the roots of most plants and that oiled grasses were sending up new growth. Indeed, Louisiana State University researcher Eugene Turner said that loss of marshland from the oil "pales in comparison" with coastal wetlands lost each year in Louisiana due to other factors, including dredging, sea level rise, sinking of land due to the removal of oil and gas, and silt capture by dams on the Mississippi River.

The ecological damage caused by the spill had measurable consequences for people. The region's mighty fisheries were shut down, forcing thousands of fishermen out of work. The government tested fish and shellfish for contamination and reopened fishing once they were found to be safe, but consumers still balked at buying Gulf seafood. Beach tourism remained low all summer as visitors avoided the region. Together, losses in fishing and tourism totaled billions of dollars.

Scientists expect some impacts of the Gulf spill to be long-lasting. Oil from the similar *Ixtoc* blowout off Mexico's coast in 1979 still lies in sediments near dead coral reefs, and fishermen there say it took 15–20 years for catches to return to normal. After the *Amoco Cadiz* spill, it took seven years for oysters and other marine species to recover. In Alaska, oil from the 1989 *Exxon Valdez* spill remains embedded in beach sand today.

However, many researchers are hopeful about the Gulf of Mexico's recovery from the *Deepwater Horizon* spill. The Gulf's warm waters and sunny climate speed the natural breakdown of oil. In hot sunlight, volatile components of oil evaporate from the surface and degrade in the water, so that fewer toxic compounds reach marine life. In addition, bacteria that consume hydrocarbons thrive in the Gulf because some oil has always seeped naturally from the seafloor and because leakage from platforms, tankers, and pipelines is common. These microbes give the region a natural self-cleaning capacity.

Researchers continue to conduct a wide range of scientific studies (**FIGURE 2**). A consortium of federal and state agencies is coordinating research and restoration efforts in the largest ever Natural Resource Damage Assessment, a process mandated under the Oil Pollution Act of 1990. Answers to questions will come to light as long-term impacts become clear.

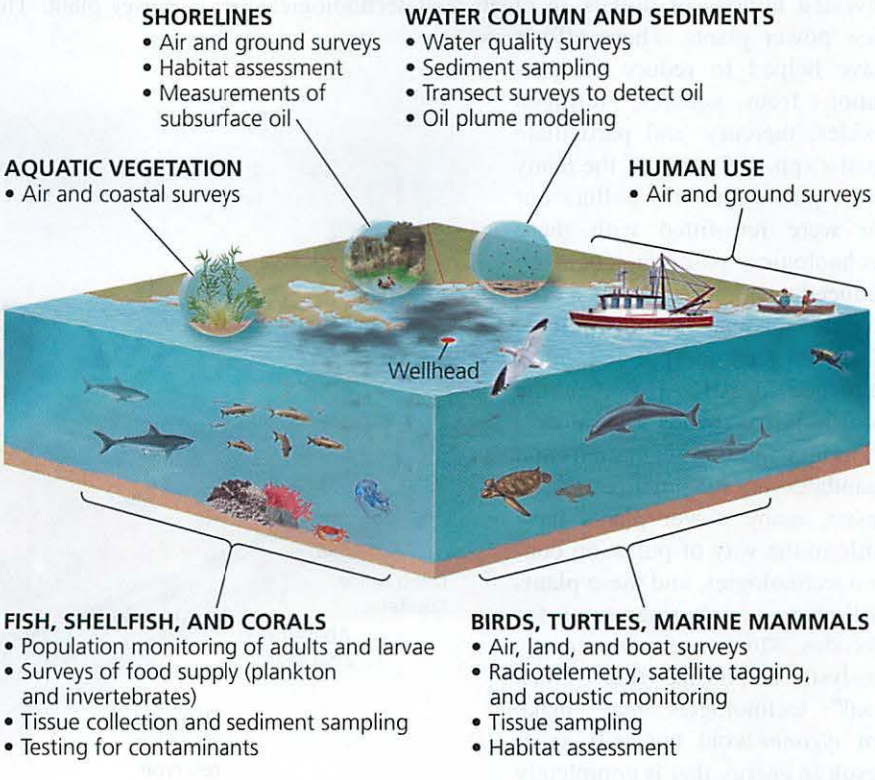


FIGURE 2 Scientific research is helping to assess damage to natural resources from the *Deepwater Horizon* oil spill. Thousands of researchers are surveying habitats, collecting samples and testing them in the lab, tracking wildlife, monitoring populations, and more.

has encouraged industry to develop and install technologies that reduce pollution, such as catalytic converters that cleanse vehicle exhaust (see Figure 17.16, p. 456).

Clean coal technologies aim to reduce air pollution from coal

At coal-fired power plants, scientists and engineers are seeking ways to cleanse coal exhaust of sulfur, mercury, arsenic, and other impurities. **Clean coal technologies** refer to an array of techniques, equipment, and approaches that aim to remove chemical contaminants during the generation of electricity from coal. Among these technologies are various types of scrubbers, devices that chemically convert or physically remove pollutants (see Figure 17.15, p. 456). Some scrubbers use minerals such as magnesium, sodium, or calcium in reactions to remove sulfur dioxide (SO_2) from smokestack emissions. Others use chemical reactions to strip away nitrogen oxides (NO_x), breaking them down into elemental nitrogen and water. Multilayered filtering devices are used to capture tiny ash particles.

Another "clean coal" approach is to dry coal that has high water content to make it cleaner-burning. We can also gain more power from coal with less pollution through gasification, in which coal is converted into a cleaner synthesis gas (called *syngas*) by reacting it with oxygen and steam at a high temperature. Syngas from coal can be used to turn a gas turbine and also to heat water to turn a steam turbine.

The U.S. government and the coal industry have each invested billions of dollars in clean coal technologies for new power plants. These efforts have helped to reduce air pollution from sulfates, nitrogen oxides, mercury, and particulate matter (pp. 455–457). If the many older plants that still pollute our air were retrofitted with these technologies, pollution could be reduced even more. This is a goal of the Obama administration's Clean Power Plan (pp. 464, 506), launched in 2015. However, the coal industry spends a great deal of money fighting regulations and mandates on its practices. As a result, many power plants have little in the way of pollution control technologies, and these plants will continue polluting our air for decades. Moreover, many energy analysts emphasize that "clean coal" technologies may make for *cleaner* coal but will never result in energy that is completely clean. Some argue that coal is an inherently dirty way of generating power and should be replaced outright with cleaner energy sources.

Can we capture and store carbon?

Even if clean coal technologies were able to remove every last contaminant from power plant emissions, coal combustion would still pump huge amounts of carbon dioxide into the air, intensifying the greenhouse effect and worsening climate change. This is why many current efforts focus on **carbon capture and storage** (CCS; p. 504). This approach involves capturing carbon dioxide emissions, converting the gas to a liquid form, and then sequestering (storing) it in the ocean or underground in a geologically stable rock formation (**FIGURE 19.21**).

Carbon capture and storage is being attempted at a variety of facilities. The world's first coal-fired power plant to approach zero emissions opened in 2008 in Germany. This plant removes its sulfate pollutants and captures its carbon dioxide, then compresses the CO_2 into liquid form, trucks it away, and injects it 900 m (3000 ft) underground into a depleted natural gas field.

In North Dakota, the Great Plains Synfuels Plant gasifies its coal, then sends half the CO_2 through a pipeline into Canada, where a Canadian oil company injects it into an oilfield to help it pump out the remaining oil. The North Dakota plant also captures, isolates, and sells seven other types of gases for various purposes.

The highest-profile effort at carbon capture and storage has suffered a rocky history. Beginning in 2003, the U.S. Department of Energy teamed up with seven energy companies to build a prototype of a near-zero-emissions coal-fired power plant. The *FutureGen* project (and its successor, the

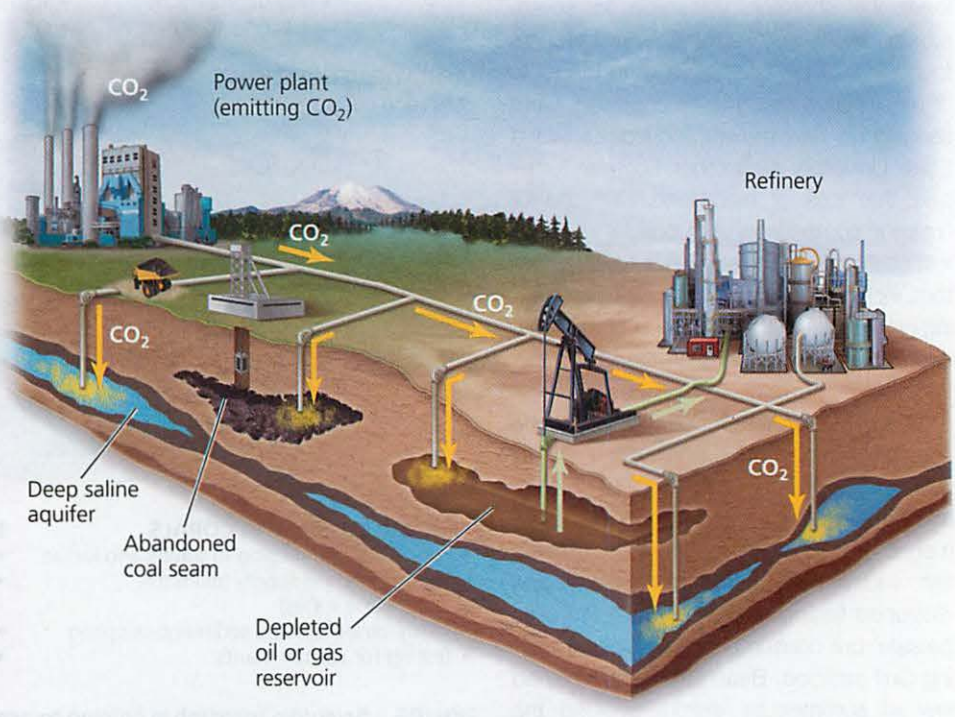


FIGURE 19.21 Carbon capture and storage schemes propose to inject liquefied carbon dioxide emissions underground. The CO_2 may be injected into depleted fossil fuel deposits, deep saline aquifers, or oil or gas deposits undergoing secondary extraction.

$1.65 billion *FutureGen 2.0*) aimed to design, construct, and operate a power plant that burns coal to generate electricity, captures 90% of its carbon dioxide emissions, and sequesters the CO_2 deep underground beneath layers of impermeable rock. It was hoped that this showcase project, located in downstate Illinois, could be a model for a new generation of power plants across the world, but financial challenges plagued it, and in 2015 the project was suspended.

weighing the ISSUES

Clean Coal and Carbon Capture

Do you think we should spend billions of dollars to try to find ways to burn coal more cleanly and to sequester carbon emissions from fossil fuels? Or is our money better spent on developing new clean and renewable energy sources, even though they don't yet have enough infrastructure to generate power at the scale that coal can? What pros and cons do you see in each approach?

At this point, carbon capture and storage remains too unproven to be the central focus of a clean energy strategy. We do not know how to ensure that carbon dioxide will stay underground once injected there. Injection might in some cases contaminate groundwater supplies or trigger earthquakes. Injecting carbon dioxide into the ocean would further acidify its waters (pp. 433, 498). Moreover, CCS is energy-intensive and decreases the EROI of coal, adding to its cost and the amount we consume. Finally, many renewable energy advocates fear that pursuing the CCS approach takes the burden off emitters and prolongs our dependence on fossil fuels rather than facilitating a shift to renewables.

We all pay external costs

The costs of addressing the many health and environmental impacts of fossil fuel extraction and use are generally not internalized in the market prices of fossil fuels. Instead, we all pay these external costs (pp. 141, 162) through medical expenses, costs of environmental cleanup, and impacts on our quality of life. Moreover, the prices we pay at the gas pump or on our monthly utility bill do not even cover the financial costs of fossil fuel extraction. Rather, fossil fuel prices have been kept inexpensive as a result of government subsidies and tax breaks to extraction companies. The profitable and well-established fossil fuel industries still receive far more financial support from taxpayers than do the young and struggling renewable energy sources (Figure 7.14, p. 179; Figure 21.7, p. 584). In this way, we all pay extra for fossil fuel energy through our taxes, generally without even realizing it.

Fossil fuel extraction has mixed consequences for local people

Wherever fossil fuels are extracted, people living nearby face the environmental, health, and social impacts of extractive development. When local people are allowed to participate in this development, however, they may also gain substantial financial benefits. In North America, communities where fossil fuel extraction takes place often experience a flush of high-paying jobs and economic activity, and for many people these economic benefits far outweigh other concerns. Perceptions can change with time, however. Economic booms generally prove temporary, lasting only as long as the resource holds out and market prices for fuel stay high. At some point all booms go bust, and once the jobs and money have left a community, its residents may be left with the legacy of a polluted environment for generations to come.

As an example, Fort McMurray has been the hub of Alberta's oil sands boom. This remote northern frontier town's population skyrocketed from 2000 in the 1960s to 80,000 as people flocked there looking for jobs. An additional 40,000 oilfield workers were being flown in and housed to work shifts, 3-weeks on, 10 days off, at the height of the recent boom. Most incoming residents have been men, averaging 32 years of age, and the city boasts the highest birth rate in Canada. Salaries are high, but so are rents and home prices. Like all boomtowns, Fort McMurray's population outgrew its infrastructure, and services became stretched thin. And like all boomtowns, it experienced a bust when the price of its principal resource fell. For Fort McMurray, the bust came in 2015 as world oil prices fell amid oversupply. Unable to make a profit on oil sands at the low prices, companies began cutting off contracts and orders and laying off workers. Across Alberta in 2015, more than 35,000 people in the energy sector lost their jobs. Still, after $200 billion of investment, many companies are in the game for the long haul, and are continuing to extract oil sands, hoping that prices will soon rise. As oil prices fluctuate in future years, Fort McMurray may see more booms and more busts.

Along the route the oil would have taken out of Alberta and through the United States via the proposed Keystone XL pipeline, TransCanada estimated that the project would have created 6500 construction jobs for two years plus 7000 one-year jobs for manufacturers of supplies. For landowners, the pipeline project would have had mixed consequences. TransCanada negotiated with thousands of landowners along the Keystone XL route, offering them money for the right to install the pipeline across their land. Many were happy to accept payments, but landowners who declined TransCanada's offers found their land rights taken away by **eminent domain**—the policy by which courts set aside private property rights to make way for projects judged to be for the public good. The landowner is paid an amount determined by a court to be fair and cannot appeal the decision.

In Alaska, the oil industry gains support for drilling by paying the Alaskan government a portion of its revenues. Since the 1970s, the state of Alaska has received more than $70 billion in oil revenues. One-quarter of these revenues are placed in the Permanent Fund, an investment fund that pays yearly dividends to all citizens. Since 1982, each Alaska resident has received annual payouts ranging from $331 to $2072.

Such distribution of revenue among citizens is unusual; in most parts of the world where fossil fuels are extracted, local residents suffer pollution without compensation. When multinational corporations pay developing nations for access to extract oil or gas, the money generally does not trickle down from government officials to the people who live where

the extraction takes place. Moreover, oil-rich developing nations such as Ecuador, Venezuela, and Nigeria tend to have few environmental regulations, and governments may not enforce regulations if doing so would jeopardize losing the large sums of money associated with oil development.

In Ecuador, local people brought suit against Chevron for environmental and health impacts from years of oil extraction in the nation's rainforests. An Ecuadorian court in 2011 found the oil company guilty and ordered it to pay $9.5 billion for cleanup—the largest-ever such judgment. Chevron refused, and the court battle proceeded to the United States, where a judge threw out the ruling. The ongoing legal battle has now moved to other nations.

In Nigeria, the Shell Oil Company extracted $30 billion of oil from land of the native Ogoni people. Oil spills, noise, and gas flares caused chronic illness among them, but oil profits went to Shell and to Nigeria's military dictatorships, while the Ogoni remained in poverty with no running water or electricity. Ogoni activist Ken Saro-Wiwa worked for fair compensation to the Ogoni. After 30 years of persecution by Nigeria's government, he was arrested in 1994 on what many believed were trumped-up charges of involvement in four murders, given a trial universally regarded as a sham, and put to death by military tribunal.

Wherever in the world fossil fuel extraction comes to communities, people find themselves divided over whether the short-term economic benefits are worth the long-term health and environmental impacts. Today this debate is occurring in North Dakota and many parts of the West in response to oil and gas drilling, and in Pennsylvania, New York, and other states above the Marcellus Shale where the petroleum industry is fracking for gas (Chapter 7). The debate has gone on for years in Appalachia over mountaintop removal mining. And along the Gulf of Mexico, the oil and gas industry employs 100,000 people and helps fund local economies—yet still more people are employed in tourism, fishing, and service industries, all of which were hurt by the *Deepwater Horizon* spill. There are no easy answers, but impacts would be lessened if extraction industries were to put more health and environmental safeguards in place for workers and residents.

Dependence on foreign energy affects economic security

Putting all your eggs in one basket is always a risky strategy. Because virtually all our modern technologies and services depend in some way on fossil fuels, we are susceptible to supplies becoming costly or unavailable. Nations that lack adequate fossil fuel reserves of their own are especially vulnerable. For instance, nations such as Germany, France, South Korea, and Japan consume far more energy than they extract and thus rely almost entirely on imports (FIGURE 19.22). In the wake of its 1970 oil extraction peak, the United States began relying more on foreign supplies.

Such reliance means that seller nations can control energy prices, forcing buyer nations to pay more as supplies dwindle. This became clear in 1973, when the **Organization of Petroleum Exporting Countries (OPEC)** resolved to stop selling oil to the United States. The predominantly Arab nations of OPEC opposed U.S. support for Israel in the Arab–Israeli Yom Kippur War and sought to raise prices by restricting supply. OPEC's embargo created panic in the West and caused oil prices to skyrocket (FIGURE 19.23), spurring

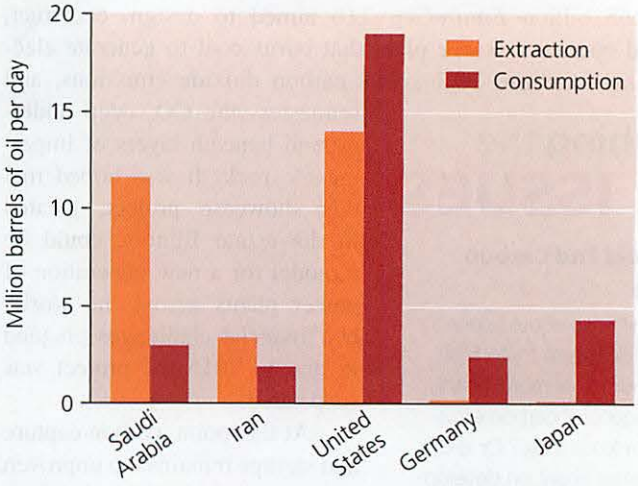


FIGURE 19.22 The United States, Germany, and Japan are among nations that consume more oil than they extract. Saudi Arabia and Iran extract more oil than they consume and are able to export oil to high-consumption countries. *Data from U.S. Energy Information Administration.*

DATA For every barrel of oil extracted in the United States, how many barrels are consumed in the United States?

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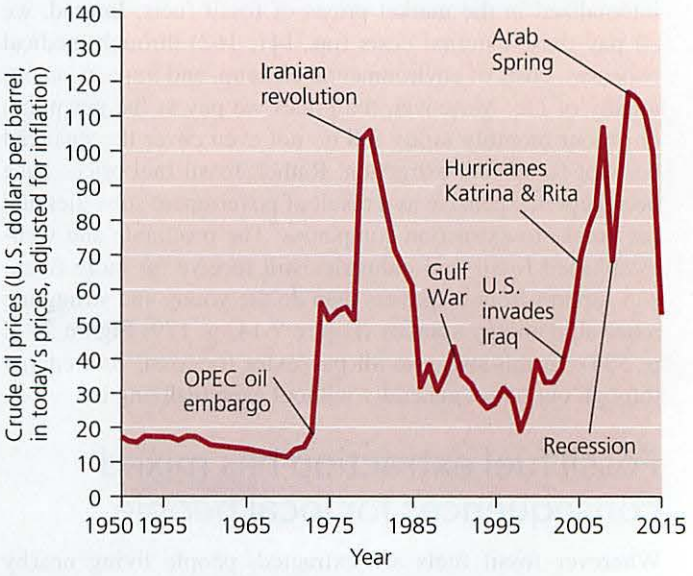


FIGURE 19.23 World oil prices have gyrated over the decades. Often this has resulted from political and economic events in oil-extracting countries, particularly in the Middle East. Prices shown are adjusted for inflation and expressed in 2015 dollars. *Data from BP p.l.c., 2016.* Statistical review of world energy 2016.

inflation. Fear of oil shortages drove Americans to wait in long lines at gas pumps. A similar supply shock occurred in 1979 in response to the Iranian revolution.

Today, experts attribute the recent fall in global oil prices to increased supply from hydraulic fracturing in the United States, followed by decisions by Saudi Arabia and OPEC to boost their own production, apparently hoping to keep prices low and drive new Western competitors out of business.

With the majority of world oil reserves located in the politically volatile Middle East, crises in this region are a constant concern for Western policymakers. The democratic street uprisings of the "Arab Spring" in 2011 put leaders of Western nations in an awkward position, because they had long supported many of the Middle East's autocratic rulers. These rulers had facilitated Western access to oil, even as they suppressed democracy in their own societies. The Arab Spring uprisings were part of a long history of events that have affected oil prices, stretching back through the two U.S.-led wars in Iraq, the Iran–Iraq war of the 1980s, and the 1973 OPEC embargo, and extending forward into recent events in Syria, negotiations with Iran over its nuclear program, and the rise of the terrorist Islamic State (ISIS).

For U.S. leaders, the troubled history of the Middle East enhances the allure of using hydraulic fracturing to boost domestic oil and gas extraction. By supplying more of its own energy, the thinking goes, the United States gains leverage internationally and becomes less susceptible to foreign entanglements. U.S. proponents of the Keystone XL pipeline used this reasoning to argue for importing petroleum from the oil sands of Canada, a stable, friendly, democratic neighboring country. However, as President Obama and others pointed out, this oil would lessen U.S. reliance on Middle Eastern nations only if it were consumed at home, whereas the plan had always been to export it. In fact, in recent years the United States has already diversified its sources of imported petroleum considerably and now receives most from non–Middle Eastern nations, including Canada, Mexico, Venezuela, and Colombia (FIGURE 19.24).

Diversifying sources of foreign oil was one way in which the United States responded to the 1973 embargo. U.S. leaders also enacted conservation measures, funded research into renewable energy, and established an emergency stockpile (which today stores one month of oil) deep underground in salt caverns in Louisiana, called the Strategic Petroleum Reserve. They also called for secondary extraction at old wells and encouraged the development of additional domestic sources.

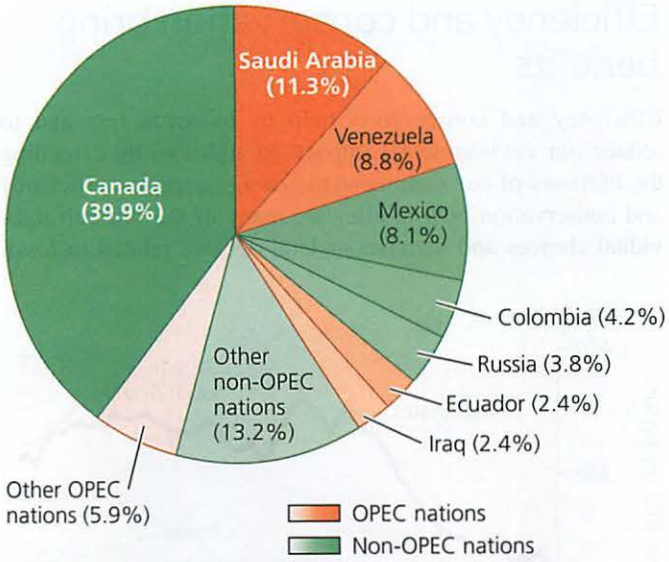


FIGURE 19.24 The United States now receives most of its imported oil from non-OPEC nations and from non–Middle Eastern nations. *Data from U.S. Energy Information Administration.*

weighing the ISSUES

Drill, Baby, Drill?

Do you think the United States should encourage hydraulic fracturing by subsidizing it and loosening regulations? Do you think the United States should open more of its offshore waters to oil and gas extraction? In each case, what benefits and costs do you foresee? Would the benefits likely exceed the costs? How strongly should government regulate oil and gas extraction once drilling begins? Give reasons for your answers.

Since then, the desire to reduce reliance on foreign oil by boosting domestic supply has driven the expansion of offshore drilling into deeper and deeper water. It has repeatedly driven a proposal to open the Arctic National Wildlife Refuge in Alaska to oil extraction, despite arguments that drilling there would spoil America's last true wilderness while adding little to the nation's oil supply. Today it is driving the push to drill for oil in Arctic waters, despite the risks. As we extend our reach for fossil fuels, our society will continue to debate the complex mix of social, political, economic, and environmental costs and benefits.

Energy Efficiency and Conservation

Because fossil fuels are in limited supply, and because their use has health, environmental, political, and socioeconomic consequences, many people have concluded that fossil fuels are not a sustainable long-term solution to our energy needs. Many see a need to shift to clean and renewable sources of energy that exert less impact on climate and human health. As our society transitions to renewable energy sources, it will benefit us to extend the availability of our fossil fuel resources. We can do so by conserving energy and by improving energy efficiency.

Energy efficiency describes the ability to obtain a given amount of output while using less energy input. **Energy conservation** describes the practice of reducing wasteful or unnecessary energy use. In general, efficiency results from technological improvements, whereas conservation stems from behavioral choices. Because greater efficiency allows us to reduce energy use, efficiency is a primary means of conservation.

Efficiency and conservation bring benefits

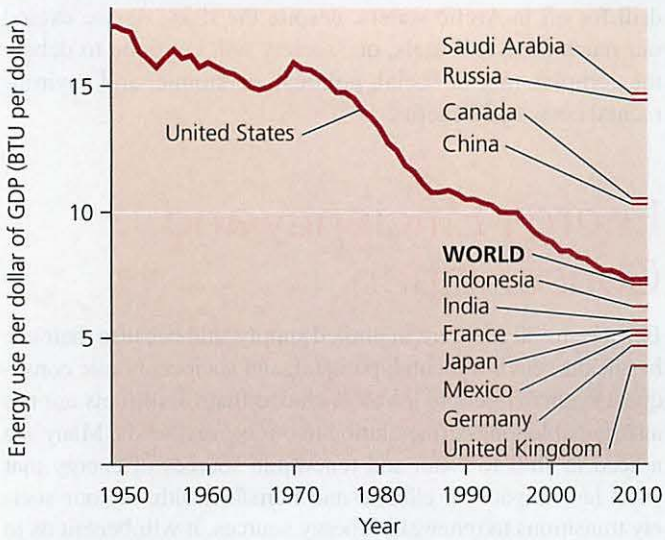
Efficiency and conservation help us to waste less and to reduce our environmental impact. In addition, by extending the lifetimes of our nonrenewable energy supplies, efficiency and conservation help to alleviate many of the difficult individual choices and divisive societal debates related to fossil fuels, from oil sands development to Arctic drilling to hydraulic fracturing.

Americans use far more energy per person than people in most other nations (FIGURE 19.25a). Citizens of many European nations enjoy standards of living similar to those of U.S. citizens yet use less energy per capita. This indicates that Americans could reduce their energy consumption considerably without diminishing their quality of life. Indeed, per-person energy consumption *has* declined slightly in the United States over the past three decades (see data line in Figure 19.26a)—and this occurred during a period of sustained economic growth.

During this period the United States also cut in half its **energy intensity,** or energy use per dollar of Gross Domestic Product (GDP) (FIGURE 19.25b). Lower energy intensity indicates greater efficiency, and these data show that the United States now gets twice as much economic bang for its energy buck. Thus, although the United States continues to burn through more energy per dollar of GDP than most other industrialized nations, Americans have achieved tremendous gains in efficiency already and should be able to make further progress.



(a) Per capita energy consumption



(b) Energy intensity

FIGURE 19.25 The United States trails other developed nations in energy efficiency but has made much progress. U.S. per-person energy use **(a)** has fallen slightly since 1979 but remains greater than that of most other nations. U.S. energy intensity **(b)** has fallen steeply and now approaches that of other developed nations. Energy intensity is energy use per inflation-adjusted 2005 dollars of GDP, using purchasing power parities, which control for differences among nations in purchasing power. *Data from U.S. Energy Information Administration.*

Personal actions and efficient technologies are two routes to conservation

As individuals, we can make conscious choices to reduce our energy consumption by driving less, dialing down thermostats, turning off lights when rooms are not in use, and investing in more energy-efficient devices and appliances. For any given individual or business, reducing energy consumption saves money while helping to conserve resources.

As a society, we can conserve energy by developing technologies and strategies to make energy-consuming devices and processes more efficient. Currently, more than two-thirds of the fossil fuel energy we use is simply lost, as waste heat, in automobiles and power plants (see Figure 19.4).

One way we can improve the efficiency of our power plants is through **cogeneration,** in which excess heat produced during the generation of electricity is captured and used to heat nearby workplaces and homes and to produce other kinds of power. Cogeneration can almost double the efficiency of a power plant. The same is true of coal gasification and combined cycle generation. In this process, coal is treated to create hot gases that turn a gas turbine, while exhaust from this turbine heats water to drive a conventional steam turbine.

In homes, offices, and public buildings, a significant amount of heat is needlessly lost in winter and gained in summer because of poor design and inadequate insulation (FIGURE 19.26). Improvements in design can reduce the energy required to heat and cool buildings. Such improvements may involve passive solar design (p. 584), better insulation, a building's location, the vegetation around it, and even the color of its roof (lighter colors keep buildings cooler by reflecting the sun's rays).



FIGURE 19.26 A thermogram reveals heat loss from buildings. It records energy in the infrared portion of the electromagnetic spectrum (p. 30). In this image, one house is uninsulated; its red color signifies warm temperatures where heat is escaping. Green shades signify cool temperatures, where heat is being conserved. Also note that in all houses, more heat is escaping from windows than from walls.

In most homes and businesses, several percent of electricity use is squandered to "vampire" power loss, energy that electronic devices in standby mode consume while switched off. However, recent government regulation has limited how much standby power devices can use, and this is reducing vampire power loss.

Many consumer products, from lightbulbs to appliances, have been reengineered through the years to enhance efficiency. Energy-efficient lighting, for example, can reduce energy use by 80%. Compact fluorescent bulbs are much more efficient than incandescent lightbulbs, which is why the United States and many other nations are phasing out incandescent bulbs.

Federal standards for energy-efficient appliances have already reduced per-person home electricity use below what it was in the 1970s. The U.S. EPA's Energy Star program (p. 504) labels refrigerators, dishwashers, and other appliances for their efficiency, enabling consumers to take energy use into account when shopping for them. Studies show that savings on utility bills readily offset the higher prices of energy-efficient appliances. The EPA estimates that if all U.S. households purchased energy-efficient appliances, the nation's annual energy expenditure would fall by $200 billion.

Automotive technology represents perhaps our best opportunity to conserve large amounts of fossil fuels fairly easily. We can accomplish this with vehicles such as electric cars, electric/gasoline hybrids, plug-in hybrids, or vehicles that use hydrogen fuel cells (p. 598). Among electric/gasoline hybrids, current U.S. models obtain fuel-economy ratings of up to about 50 miles per gallon (mpg)—twice that of the average American car. Many fully electric vehicles now obtain fuel-economy ratings of over 100 mpg. Automakers also possess the means to enhance fuel efficiency for traditional gasoline-powered vehicles further by using lightweight materials, continuously variable transmissions, and more efficient engines.

Automobile fuel efficiency is a key to conservation

One of the ways in which U.S. leaders responded to the OPEC embargo of 1973 was to mandate an increase in the fuel efficiency of automobiles. Over the next three decades, however, as market prices for oil fell, many of the conservation initiatives of this time were abandoned. Without high market prices and an immediate threat of shortages, people lacked economic motivation to conserve, and U.S. policymakers repeatedly failed to raise the corporate average fuel efficiency (CAFE) standards, which set benchmarks for auto manufacturers to meet. The average fuel efficiency of new vehicles fell from 22.0 mpg in 1987 to 19.3 mpg in 2004, as sales of sport-utility vehicles increased relative to sales of cars.

In 2007, Congress mandated that automakers raise average fuel efficiency to 35 mpg by the year 2020. Since 2007, fuel economy has climbed substantially (**FIGURE 19.27**). Yet despite this advance, American automobiles continue to lag behind the vehicles of most other developed nations. When automakers requested a government bailout during the recent recession, President Obama forced them to agree to boost average fuel economies to 54.5 mpg by 2025. If this improvement comes to pass, it will enable a huge reduction in oil use. New technologies will add more than $2000 to the average price of a car, but drivers will save perhaps $6000 in fuel costs over the car's lifetime.

In 2009, Congress and the Obama administration took another major step to improve automobile fuel efficiency

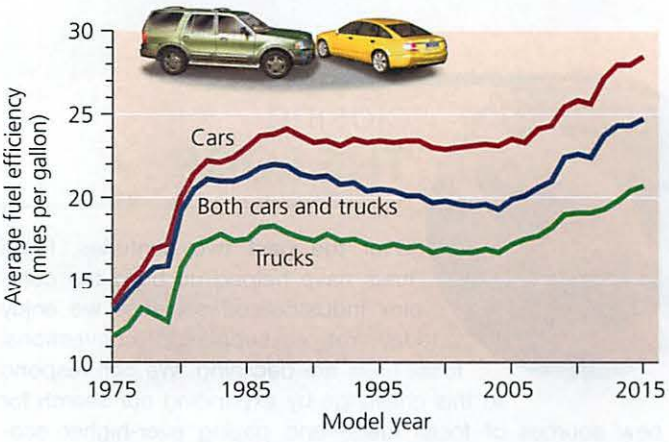


FIGURE 19.27 Automotive fuel efficiencies have responded to public policy. Fuel efficiency for automobiles in the United States rose dramatically in the late 1970s as a result of legislative mandates but then stagnated when no additional laws were enacted to improve fuel economy. Recent legislation is once again improving fuel efficiency. *Data from U.S. Environmental Protection Agency, 2015.* Light-duty automotive technology, carbon dioxide emissions, and fuel economy trends: 1975 through 2015.

while stimulating economic activity and saving jobs during a severe recession. The popular "Cash for Clunkers" program—formally named the Consumer Assistance to Recycle and Save (CARS) Act—paid Americans $3500 or $4500 each to turn in old vehicles and purchase newer, more fuel-efficient ones. The $3 billion program subsidized the sale or lease of 678,000 vehicles averaging 24.9 mpg that replaced vehicles averaging 15.8 mpg. It is estimated that 824 million gallons of gasoline are being saved as a result, preventing 9 million metric tons of greenhouse gas emissions and creating social benefits worth $278 million.

U.S. policymakers could do more to encourage oil conservation. The United States has kept taxes on gasoline extremely low, relative to most other nations. Americans pay two to three times *less* per gallon of gas than drivers in many European countries. In fact, gasoline in the United States is sold more cheaply than bottled water! As a result, U.S. gasoline prices do not account for the substantial external costs (pp. 141, 162) that oil extraction and consumption impose on society. Some experts estimate that if all costs to society were taken into account, the price of gasoline would exceed $13 per gallon. Instead, our artificially low gas prices diminish our economic incentive to conserve.

weighing the ISSUES

More Miles, Less Gas

If you drive an automobile, what gas mileage does it get? How does it compare to the vehicle averages in Figure 19.27? If your vehicle's fuel efficiency were 10 mpg greater, and if you drove the same amount, how many gallons of gasoline would you no longer need to purchase each year? How much money would you save?

Do you think U.S. leaders should mandate further increases in the CAFE standards? Should the government raise taxes on gasoline sales as an incentive for consumers to conserve energy? What effects on economics, on health, and on environmental quality might each of these steps have?

The rebound effect cuts into efficiency gains

Energy efficiency is a vital pursuit, but it may not always save as much energy as we expect. This is because gains in efficiency from better technology may be partly offset if people engage in more energy-consuming behavior as a result. For instance, a person who buys a fuel-efficient car may choose to drive more because he or she feels it's okay to do so (or because he or she can afford to) now that less gas is being used per mile. This phenomenon is called the **rebound effect,** and studies indicate that it is widespread and significant. In some instances, the rebound effect may completely erase efficiency gains. As our society pursues energy efficiency, this will be an important factor to consider.

We need both conservation and renewable energy

Despite concerns over the rebound effect, energy efficiency and conservation efforts are vital to creating a sustainable future for our society. It is often said that reducing our energy use is equivalent to finding a new oil reserve. Some estimates hold that energy conservation and efficiency in the United States could save 6 million barrels of oil a day—nearly the amount gained from all offshore drilling, and considerably more than would be gained from Canada's oil sands. In fact, conserving energy is *better* than finding a new reserve because it alleviates health and environmental impacts while at the same time extending our future access to fossil fuels.

Yet regardless of how effectively we conserve, we will still need energy to power our civilization, and it will need to come from somewhere. Most energy experts maintain that the only sustainable way of guaranteeing ourselves a reliable long-term supply of energy is to ensure sufficiently rapid development of renewable energy sources (Chapters 20 and 21).



closing THE LOOP

Over the past two centuries, fossil fuels have helped us build the complex industrialized societies we enjoy today. Yet our supplies of conventional fossil fuels are declining. We can respond to this challenge by expanding our search for new sources of fossil fuels—and paying ever-higher economic, health, and environmental costs. Or, we can encourage conservation and efficiency while developing alternative energy sources that are clean and renewable. The path we choose will have far-reaching consequences for human health and well-being, for Earth's climate, and for the stability and progress of our civilization.

The debate over the Canadian oil sands and the Keystone XL pipeline has been a microcosm of this larger conversation over our energy future. In all likelihood, the long-running debate over oil sands extraction and transport will have taken a few more turns by the time you read this book. We encourage you to research the latest developments, discuss them with your instructor, and wrestle thoughtfully with the issues.

Our modern energy situation is complex, but fortunately we are not caught in a simple trade-off between fossil fuels' economic benefits and their impacts on the environment, climate, and health. Instead, as renewable energy sources become increasingly well developed and economical, it becomes easier to envision freeing ourselves from a reliance on fossil fuels and charting a bright future for humanity and the planet with renewable energy.

REVIEWING Objectives

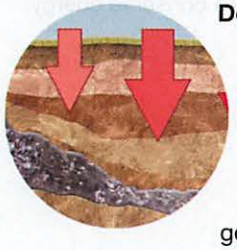
You should now be able to:

Identify the energy sources that we use

Many energy sources are available, but since the industrial revolution, nonrenewable fossil fuels—including coal, natural gas, and oil—have become our primary sources of energy. We are also developing alternative sources of clean and renewable energy. (pp. 517–519)

Discuss the value of the EROI concept

The concepts of *net energy* and *EROI* allow us to compare the amount of energy obtained from a source with the amount invested in its extraction and processing. This can help decide which energy sources are most efficient and productive. (pp. 519–520)



Describe the formation of major types of fossil fuels

Fossil fuels are formed very slowly as buried organic matter is chemically transformed by heat, pressure, and/or anaerobic decomposition. Coal results from organic matter that undergoes compression but little decomposition. Crude oil is a thick, liquid mixture of hydrocarbons formed under high temperature and pressure. Natural gas consists mostly of methane and can be formed in two ways. Oil sands contain bitumen, a tarry substance formed from oil degraded by bacteria, whereas shale oil and methane hydrate are other unconventional sources with future potential. (pp. 520–524)

Explain how we extract, process, and use fossil fuels



Scientists locate fossil fuel deposits by analyzing subterranean geology. Coal is mined underground and strip-mined from the surface, whereas we drill wells to pump out oil and gas. Oil sands may be strip-mined or dissolved underground and extracted through well shafts. Refineries separate components of crude oil to transform it into a wide variety of fuel types. Coal and natural gas are used today principally to generate electricity. Oil powers transportation and also is used to create a diversity of petroleum-based products. (pp. 522–527)

Assess concerns over the future decline of conventional oil supplies

Any nonrenewable resource can be depleted, and we have depleted nearly half the world's conventional oil. Once we pass the peak of oil extraction, the gap between rising demand and falling supply may pose immense challenges for society. (pp. 527–529)

Outline ways in which we are extending our reach for fossil fuels

The conventional fossil fuels that remain unexploited are harder to access and more expensive to extract, so we are applying technology and new approaches to extract them, including mountaintop removal mining, secondary extraction, directional drilling, hydraulic fracturing, deep offshore drilling, and Arctic exploration. We are also beginning to mine unconventional fossil fuels such as oil sands. (pp. 529–532)



Examine environmental impacts of fossil fuel use, and explore ways to minimize these impacts

In various ways, coal mining, oil and gas drilling, and oil sands extraction can alter ecosystems, pollute air and waterways, and pose health risks. Hydraulic fracturing magnifies some of these impacts. Fuels can also spill during transport, affecting soil, water, wildlife, and health. Emissions from fossil fuel combustion pollute air, pose human health risks, and drive global climate change. Public policy and advances in pollution control technology have reduced many of these emissions, but much more remains to be done. If we could safely capture carbon dioxide and sequester it underground, this would resolve a primary drawback of fossil fuels, but carbon capture and storage remains unproven so far. (pp. 532–539)

Assess political, social, and economic aspects of fossil fuel use

Fossil fuels impose a variety of external costs. Fossil fuel extraction creates jobs but leaves pollution. People living in areas of extraction experience a range of consequences. Today's societies are heavily reliant on fossil fuel energy, and nations that consume far more fossil fuels than they extract are especially vulnerable to supply restrictions. (pp. 539–541)

Discuss strategies for conserving energy and enhancing efficiency



Energy conservation involves both personal choices and efficient technologies. Efficiency in power plant combustion, lighting, consumer appliances, and automotive fuel efficiency all play roles in conserving energy. The rebound effect, however, can partly negate our conservation efforts. Conservation lengthens our access to fossil fuels and reduces environmental impact, but to build a sustainable society we will also need to shift to renewable energy sources. (pp. 541–544)

TESTING Your Comprehension

1. Name one reason that fossil fuels are our most prevalent source of energy today. Why are fossil fuels considered nonrenewable?
2. Describe how *net energy* differs from *energy returned on investment (EROI)*. Why are these concepts important when evaluating energy sources?
3. How are fossil fuels formed? How do environmental conditions determine which type of fossil fuel is formed in a given location? Why are fossil fuels often concentrated in localized deposits?
4. How do *technically recoverable* and *economically recoverable* amounts of a resource differ? Define the term *proven recoverable reserve*. Explain why the proven recoverable reserve of a given fuel could increase over time. Now explain why it could decrease.
5. Describe how coal is used to generate electricity.
6. How do we create petroleum products? Provide examples of several of these products.
7. Why do many experts think we are about to pass the global extraction peak for conventional oil? What consequences might there be for our society? What are two fundamental ways that we could respond to *peak oil*?
8. Describe three ways in which we are now extending our reach for fossil fuels. List several impacts (positive or negative) that these actions might have.
9. Give an example of a clean coal technology. Now describe how carbon capture and storage is intended to work.
10. Describe two specific examples of how technological advances can improve energy efficiency. Now describe one specific action you could take to conserve energy.

SEEKING Solutions

1. Describe three specific health or environmental impacts of fossil fuel extraction or consumption. For each impact, what steps could governments, industries, or individuals take to alleviate the impact?
2. Contrast the experiences of the Ogoni people of Nigeria with those of the citizens of Alaska. How have they been similar and different? Do you think businesses or governments should take steps to ensure that local people benefit from oil drilling operations? How could they do so?
3. Based on data in this chapter, explain two reasons why it is reasonable to expect that Americans should be able to use energy more efficiently in the future as the U.S. economy expands.
4. **CASE STUDY CONNECTION** Summarize the main arguments for and against the Keystone XL pipeline extension. What problems might the pipeline have helped solve? What problems might it have created? Do you personally think Canada should continue to develop Alberta's oil sands? Should the United States have approved construction of the Keystone XL pipeline extension? Give reasons for your answers.
5. **THINK IT THROUGH** You are the mayor of a rural Nebraska town along the route of the proposed Keystone XL pipeline, and a new U.S. presidential administration has reversed President Obama's decision and invited TransCanada to build the pipeline extension. Some of your town's residents are eager to have jobs they believe the pipeline will bring. Others are fearful that oil leaks from the pipeline could contaminate the water supply. Some of your town's landowners are looking forward to receiving payments from TransCanada for use of their land, whereas others dread the prospect of noise, pollution, and trees being cut on their property. If the company receives too much local opposition, it says it may move the pipeline route away from your town. What information would you seek from TransCanada, from your state regulators, and from scientists and engineers before deciding whether support for the pipeline is in the best interest of your town? How would you make your decision? How might you try to address the diverse preferences of your town's residents?
6. **THINK IT THROUGH** You are elected governor of the state of Florida as the federal government is debating opening new waters to offshore drilling for oil and natural gas. Drilling in Florida waters would create jobs for Florida citizens and revenue for the state in the form of royalty payments from oil and gas companies. However, there is always the risk of a catastrophic oil spill, with its ecological, social, and economic impacts. Would you support or oppose offshore drilling off the Florida coast? Why? What, if any, regulations would you insist be imposed on such development? What questions would you ask of scientists before making your decision? What factors would you consider in making your decision?

CALCULATING Ecological Footprints

Scientists at the Global Footprint Network calculate the energy component of our ecological footprint by estimating the amount of ecologically productive land and sea required to absorb the carbon released from fossil fuel combustion. This translates into 5.9 hectares (ha) of the average American's 8.2-ha ecological footprint. Another way to think about our footprint, however, is to estimate how much land would be needed to grow biomass with an energy content equal to that of the fossil fuel we burn.

Assume that you are an average American who burns about 6.1 metric tons of oil-equivalent in fossil fuels each year and that average terrestrial net primary productivity (p. 111) can be expressed as 0.0037 metric ton/ha/year. Calculate how many hectares of land it would take to supply our fuel use by present-day photosynthetic production.

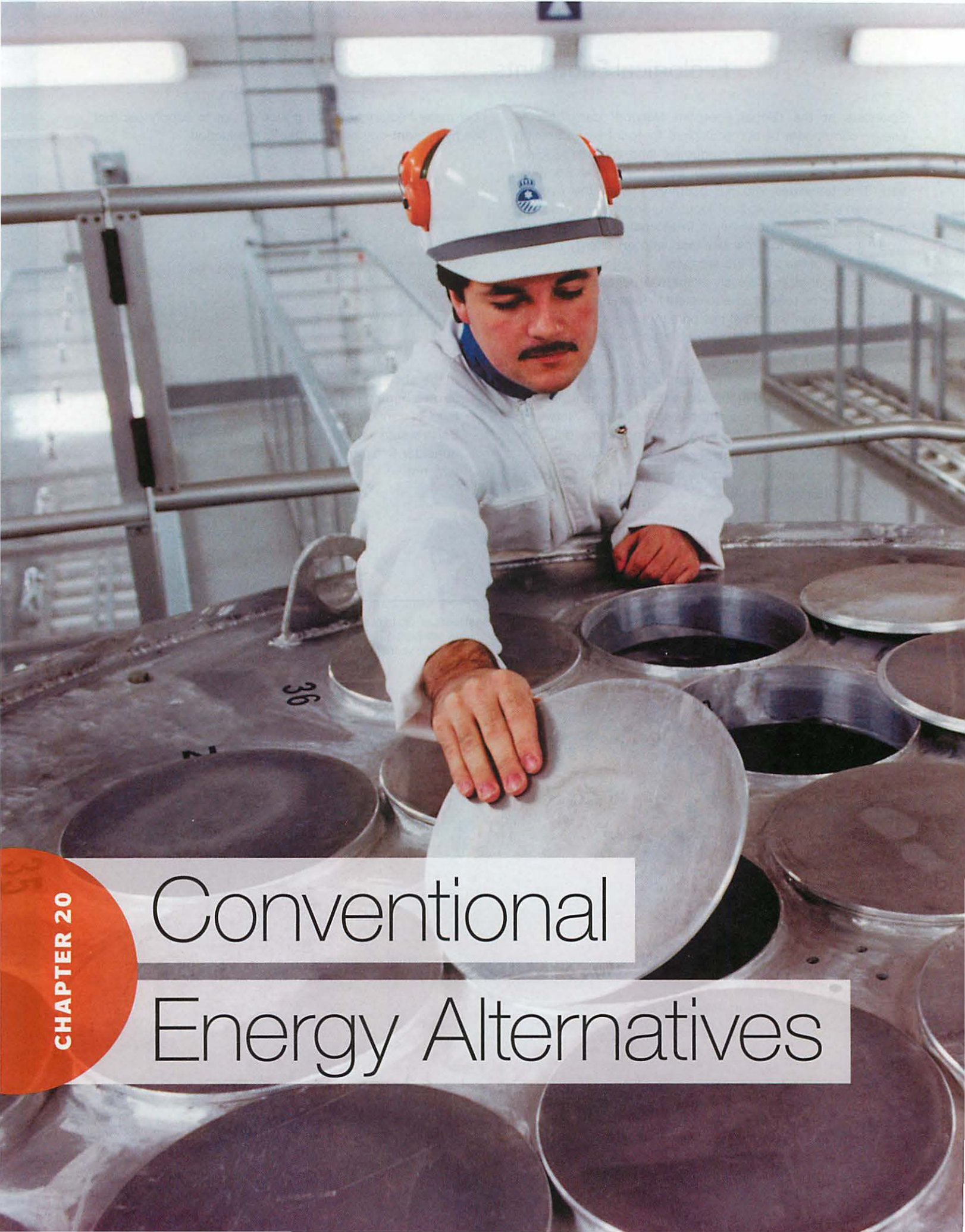
	HECTARES OF LAND FOR FUEL PRODUCTION
You	1649
Your class	
Your state	
United States	

1. Compare the energy component of your ecological footprint calculated in this way with the 5.9 ha calculated using the method of the Global Footprint Network. Explain why results from the two methods may differ.
2. Earth's total land area is approximately 15 billion hectares. Compare this to the hectares of land for fuel production from the table.
3. In the absence of stored energy from fossil fuels, how large a human population could Earth support at the level of consumption of the average American, if all of Earth's area were devoted to fuel production? Do you consider this realistic? Provide two reasons why or why not.

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CHAPTER 20

Conventional Energy Alternatives

central
CASE STUDY

Will Sweden Free Itself of Fossil Fuels?



> **Sweden will become one of the first fossil [fuel]-free . . . states in the world.**
> Swedish Prime Minister Stefan Löfven, 2015

> **If [Sweden] phases out nuclear power, then it will be virtually impossible for the country to keep its climate-change commitments.**
> Yale University economist William Nordhaus, 1997

Flashback to 1986: On the morning of April 28, alarms went off at a nuclear power plant in Sweden, as sensors detected unusually high levels of radiation. However, the radioactivity had not come from within the plant. Instead, it had spread through the atmosphere from the Soviet Union. The workers at this Swedish power plant had discovered the outside world's first evidence of the disaster at Chernobyl, more than 1200 km (750 mi) away in what is now the nation of Ukraine. Chernobyl's nuclear reactor had exploded two days earlier, the result of human error and unsafe engineering, but the Soviet government had not yet admitted it.

Fast-forward to 2011: On March 11, seismometers in Sweden and throughout the world recorded vibrations from the shaking of the massive Tohoku earthquake off the coast of Japan. Soon thereafter, a tsunami inundated the Japanese coast, destroying entire towns, killing more than 18,000 people, and disabling nuclear reactors at the Fukushima Daiichi power plant. For the next several weeks, the world would stand on edge as Japanese authorities frantically tried to control the leakage of radiation from the plant and avert further catastrophe.

The events at both Chernobyl and Fukushima had broad and long-lasting repercussions. Each altered the course of the world's use of nuclear energy, one of our main alternatives to fossil fuels. While people in Ukraine and Japan still struggle with the legacies of these events, the global debate over nuclear power affects all of us.

In Sweden in the days after Chernobyl, low levels of radioactive fallout rained down on the countryside, contaminating crops and cows' milk. For many Swedes, this confirmed the decision they had made collectively six years earlier, in a 1980 referendum, to phase out their country's nuclear power program, shutting down all nuclear plants by the year 2010.

But trying to phase out nuclear power proved difficult. Sweden had turned to nuclear power as it sought to reduce its use of coal, oil, and natural gas because of the health and environmental impacts of fossil fuels. Sweden became one of the few nations in the world to decrease its reliance on fossil fuels (**FIGURE 20.1**, p. 550). The nation has cut its fossil fuel use in half since the 1970s, while boasting a thriving economy that continues to provide its citizens with one of the highest living standards on Earth. Sweden accomplished this largely by replacing fossil-fuel-fired electricity with nuclear power—and



Using biogas to fuel vehicles in Kristianstad, Sweden ▲

Upon completing this chapter, you will be able to:

- Discuss the reasons for seeking energy alternatives to fossil fuels
- Summarize the contributions to world energy supplies of conventional alternatives to fossil fuels
- Describe nuclear energy and explain how we harness it for electrical power
- Assess the benefits and drawbacks of nuclear power, and discuss the societal debate over this energy source
- Describe established and emerging sources and techniques involved in harnessing bioenergy, and assess bioenergy's benefits and shortcomings
- Outline the scale, methods, and impacts of hydroelectric power

Technician inside a nuclear power plant near Stockholm, Sweden

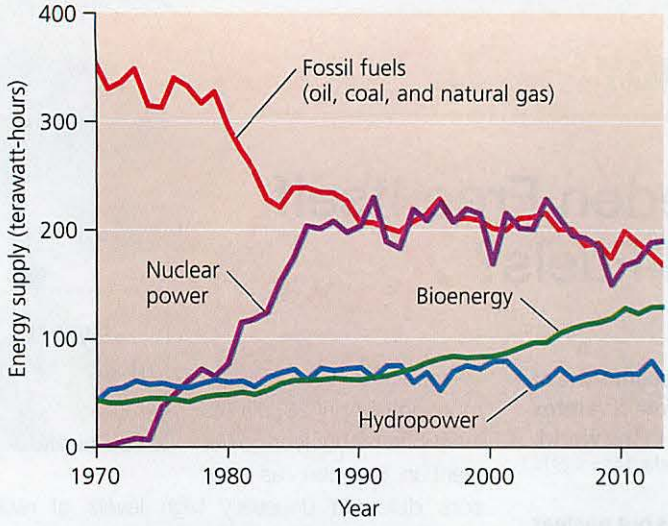


FIGURE 20.1 Sweden has greatly reduced its use of fossil fuels (mostly oil) since 1970. In their place, it has increased its use of nuclear power, hydroelectric power, and bioenergy. *Data from Swedish Energy Agency.*

DATA Based on the data in the graph, articulate a causal hypothesis regarding which energy source—nuclear power, hydropower, or bioenergy—was most responsible for taking the place of fossil fuels in Sweden. Explain the logic behind your hypothesis by referencing patterns in the data.

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as 2010 drew nearer, Sweden was still relying on 10 nuclear reactors for more than 30% of its energy supply and more than 40% of its electricity. If nuclear plants were to be shut down as planned, without reverting to fossil fuels, then the nation would need to boost its investment in alternative energy sources dramatically.

As a result, Sweden threw its weight behind research and development of renewable energy sources. Hydroelectric power was already supplying most of the rest of the nation's electricity and could not be expanded much more. Instead, the government hoped that energy from biomass sources and wind power could fill the gap. Manipulating market forces to make fossil fuels more expensive and renewable energy more affordable, Sweden boosted bioenergy and wind by applying a carbon tax (p. 509) to fossil fuels and by subsidizing renewable energy through a certificate program in which producers and users of fossil fuel electricity were mandated to buy certificates from producers and users of renewable electricity.

Sweden soon built itself into an international leader in renewable energy, and today gets more than half its energy from renewable sources. Still, renewables took longer to develop than hoped, so policymakers repeatedly postponed the nuclear phaseout. In 2009, just before the original self-imposed deadline, the Swedish government announced that it was reversing its policy and would not phase out nuclear power after all. Instead, new power plants would be built as existing ones needed replacing.

In announcing this decision, Sweden's leaders said it would be fiscally and socially irresponsible to dismantle the nation's nuclear program without a ready replacement. Without an abundance of clean renewable power, a nuclear phaseout would mean a return to fossil fuels, or else would require cutting down immense areas of forest to combust biomass. Policymakers also cited Sweden's international obligations to hold down its carbon emissions under the Kyoto Protocol (p. 506). They reminded citizens that nuclear power is free of atmospheric pollution and is an effective way to minimize the greenhouse gas emissions that drive climate change.

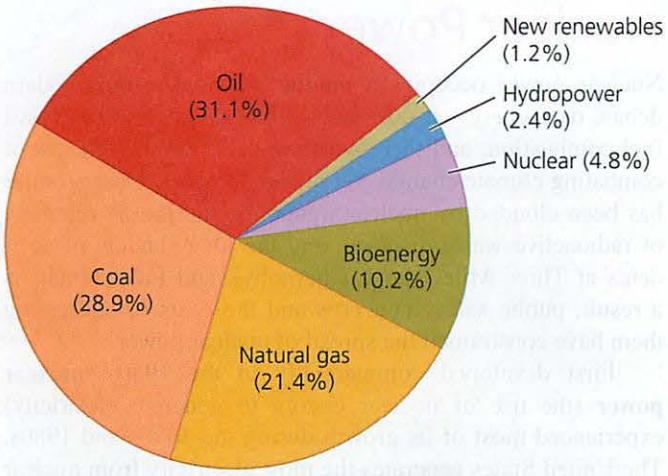
Then Fukushima occurred. As the drama played out in Japan, anti-nuclear protestors all over the world staged demonstrations. Many national governments reassessed their commitments to nuclear power, ran safety checks of existing plants, and halted plans for new plants.

The Swedish government's shifting policies have reflected changing public sentiments. The majority of Swedes have always seen the clear benefits of fighting pollution and climate change by developing energy sources such as nuclear power, bioenergy, and hydropower, and they are proud of having moved so decisively away from fossil fuels. Yet each nuclear accident has eroded otherwise strong public support for nuclear power.

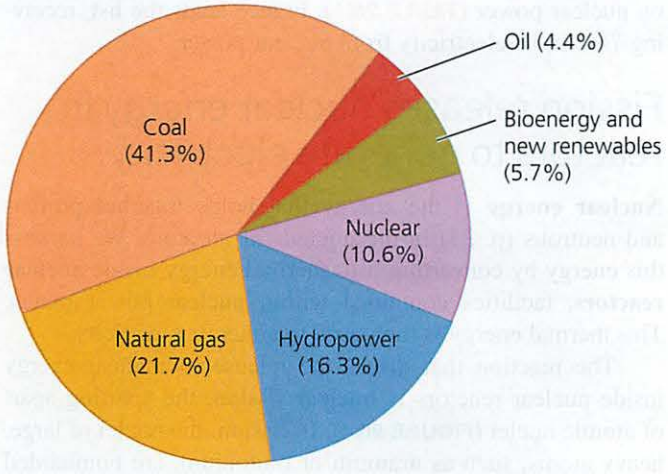
In 2015, Sweden's new prime minister, Stefan Löfven, announced that his government would aim one day to make Sweden completely free of fossil fuels. This proclamation was accompanied by an announcement of $550 million in new public funding toward renewable energy sources such as wind power, solar power, hydropower, and bioenergy. Time will tell the fate of nuclear power in Sweden, but that nation's citizens and leaders continue to support boosting the development of renewable energy sources to keep their nation a world leader in the shift away from fossil fuels.

Alternatives to Fossil Fuels

Fossil fuels drove the industrial revolution and helped to create the unprecedented material prosperity we enjoy today. Our global economy is powered largely by fossil fuels; more than 80% of our energy comes from oil, coal, and natural gas (**FIGURE 20.2a**). These three fuels also generate two-thirds of the world's electricity (**FIGURE 20.2b**). However, easily extractable supplies of these nonrenewable energy sources are in decline, and we are expending more and more energy and money to extract them (pp. 529–532). Moreover, the use of coal, oil, and natural gas drives global climate change and entails many other impacts to human health, society, and the environment (Chapters 17, 18, and 19).



(a) World energy consumption, by source



(b) World electricity generation, by source

FIGURE 20.2 Fossil fuels dominate the global energy supply. Together, oil, coal, and natural gas account for 81% **(a)** of the world's energy consumption. Nuclear power and hydroelectric power contribute substantially to global electricity generation **(b)**, but fossil fuels still power two-thirds of our electricity. *Data from International Energy Agency, 2015.* Key world energy statistics 2015. *Paris: IEA.*

For these reasons, most energy experts accept that we will need to shift from fossil fuels to energy sources that are less easily depleted and gentler on our health and environment. Developing alternatives to fossil fuels has the added benefit of helping to diversify an economy's mix of energy, thus lessening price volatility and dependence on foreign fuel imports.

We have developed a range of alternatives to fossil fuels (see Table 19.1, p. 517). Most of these energy sources are renewable, and most have less impact on health and the environment than oil, coal, or natural gas. Currently, most remain more expensive than fossil fuels, at least in the short term and when external costs (pp. 141, 162) are not included in market prices. Yet as technologies develop and as we invest in infrastructure to better transmit power from renewable sources, prices will continue to fall, helping us to transition toward these alternative energy sources.

Nuclear power, bioenergy, and hydropower are conventional alternatives

Three alternative energy sources are currently the most developed and most widely used: nuclear power, hydroelectric power, and energy from biomass. These energy sources are well established, and each of them already plays a substantial role in our energy and electricity budgets. As a result, we can therefore describe nuclear power, hydropower, and biomass energy (bioenergy) as "conventional alternatives" to fossil fuels.

Each of these three conventional energy alternatives is generally considered to exert less environmental impact than fossil fuels but more impact than "new renewable" alternatives such as solar, wind, geothermal, and ocean power (Chapter 21). Yet as we will see, each of our conventional energy alternatives involves a unique and complex mix of benefits and drawbacks. Nuclear power is commonly considered a nonrenewable energy source, and hydropower and bioenergy are generally described as renewable, but the reality is more complicated.

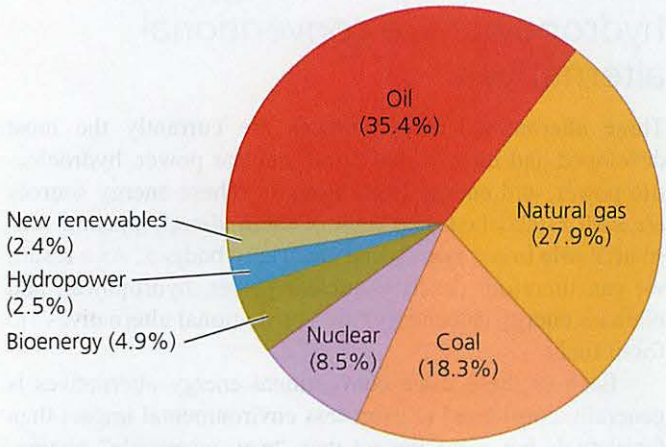
Sweden has shown that it is possible for a wealthy and advanced economy to replace fossil fuels gradually with these conventional alternative sources while continuing to raise living standards for its citizens. Since 1970, Sweden has decreased its fossil fuel use from 81% to 30% of its national energy budget (see Figure 20.1). Today the three conventional alternatives—nuclear power, bioenergy, and hydropower—together provide Sweden with two-thirds of its energy and virtually all of its electricity.

Conventional alternatives provide much of our electricity

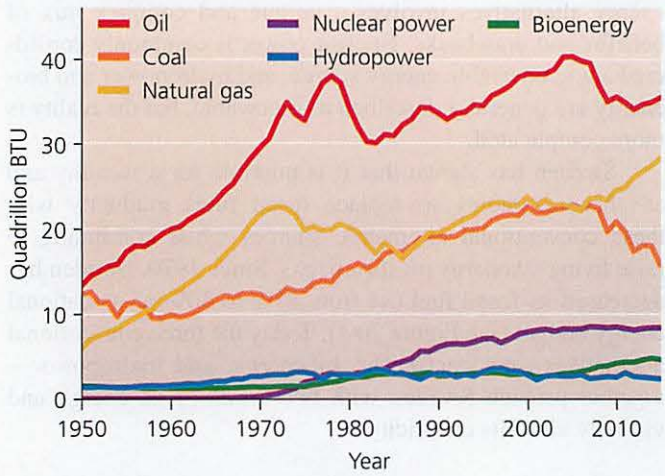
Across the globe, fuelwood and other bioenergy sources provide 10% of the world's energy, nuclear power provides about 5%, and hydropower provides about 2%. By comparison, the less established "new renewable" energy sources together account for just over 1% (see Figure 20.2a). Although their global contributions to our overall energy supply so far are minor, alternatives to fossil fuels do contribute greatly to our generation of electricity. Nuclear energy and hydropower together account for about 27% of the world's electricity generation (see Figure 20.2b).

Energy consumption patterns in the United States (**FIGURE 20.3a**, p. 552) are similar to those globally, except that the United States relies less on fuelwood and slightly more on fossil fuels and nuclear power than most other countries. A graph showing trends in energy consumption in the

United States over the past 65 years (FIGURE 20.3b) reveals two things. First, conventional alternatives play minor yet substantial roles in overall energy use. Second, use of conventional alternatives has been growing more slowly than use of fossil fuels.



(a) U.S. energy consumption, by source



(b) U.S. energy consumption, 1950–2015

FIGURE 20.3 Fossil fuels predominate in the United States. Together, oil, natural gas, and coal account for 82% **(a)** of U.S. energy consumption. The line graph **(b)** shows amounts of each energy source used in the United States across the past 65 years. *Data from U.S. Energy Information Administration, 2016.*

DATA Americans use more of every energy source than they did 65 years ago, but usage patterns have varied.

- Since 1950, which energy source has grown the most, in absolute terms?
- Since 1950, which energy source has grown the most, in percentage terms?
- Which two energy sources grew fastest between 1950 and 1970?
- Which two energy sources grew fastest between 1970 and 1990?
- For each of the six energy sources shown, explain what has happened with their usage since 1990.

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Nuclear Power

Nuclear power occupies a unique position in our modern debate over energy. It does not pollute the air as does fossil fuel combustion, and thereby offers us a powerful means of combating climate change. Yet nuclear power's great promise has been clouded by nuclear weaponry, the thorny dilemma of radioactive waste disposal, and the long shadow of accidents at Three Mile Island, Chernobyl, and Fukushima. As a result, public safety concerns and the costs of addressing them have constrained the spread of nuclear power.

First developed commercially in the 1950s, **nuclear power** (the use of nuclear energy to generate electricity) experienced most of its growth during the 1970s and 1980s. The United States generates the most electricity from nuclear power of any nation—more than a quarter of the world's production—yet less than 20% of U.S. electricity comes from nuclear power. A number of other nations rely more heavily on nuclear power (TABLE 20.1). France leads the list, receiving 76% of its electricity from nuclear power.

Fission releases nuclear energy in reactors to generate electricity

Nuclear energy is the energy that holds together protons and neutrons (p. 23) in the nucleus of an atom. We harness this energy by converting it to thermal energy inside **nuclear reactors,** facilities contained within nuclear power plants. This thermal energy is then used to generate electricity.

The reaction that drives the release of nuclear energy inside nuclear reactors is **nuclear fission,** the splitting apart of atomic nuclei (FIGURE 20.4). In fission, the nuclei of large, heavy atoms, such as uranium or plutonium, are bombarded

TABLE 20.1 Top Producers of Nuclear Power

NATION	NUCLEAR POWER CAPACITY (gigawatts)	NUMBER OF REACTORS	ELECTRICITY FROM NUCLEAR POWER (%)
United States	99.2	99	19.5
France	63.1	58	76.3
Japan	42.4	48	0.5
China	26.8	31	3.0
Russia	25.4	35	18.6
South Korea	21.7	24	31.7
Canada	13.5	19	16.6
Ukraine	13.1	15	56.5
Germany	12.1	9	14.1
Sweden	9.6	10	34.3

Data from International Atomic Energy Agency.

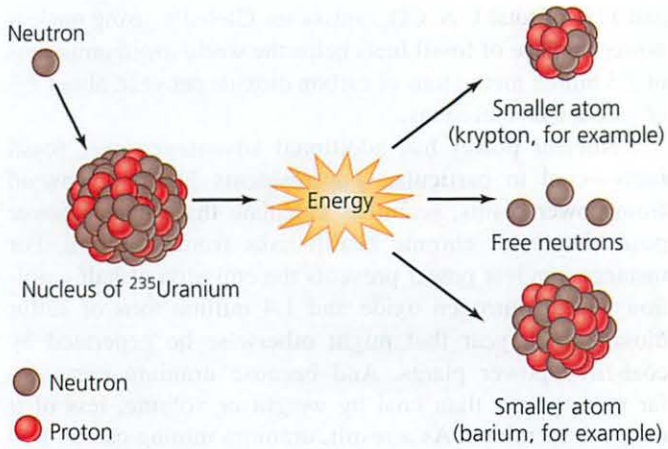


FIGURE 20.4 Nuclear fission drives modern nuclear power. In nuclear fission, the nucleus of an atom of uranium-235 is bombarded with a neutron. The collision splits the uranium atom into smaller atoms and releases two or three neutrons, along with energy in the form of heat, light, and radiation.

with neutrons. Ordinarily, neutrons move too quickly to split nuclei when they collide with them, but if neutrons are slowed down they can break apart nuclei. In a nuclear reactor, the neutrons bombarding uranium are slowed down with a substance called a *moderator*, most often water or graphite. Each split nucleus emits energy in the form of heat, light, and radiation, and also releases neutrons. These resulting neutrons (two to three per nucleus in the case of uranium-235) can in turn bombard other nearby uranium-235 (^{235}U) atoms, resulting in a self-sustaining chain reaction.

If not controlled, this chain reaction becomes a runaway process of positive feedback (p. 104)—the process that creates the explosive power of a nuclear bomb. Inside a nuclear power plant, however, fission is controlled so that, on average, only one of the two or three neutrons emitted with each fission event goes on to induce another fission event. To soak up the excess neutrons produced when uranium nuclei divide, control rods made of a metallic alloy that absorbs neutrons are placed among the water-bathed fuel rods of uranium. Engineers move these control rods into and out of the water to maintain the fission reaction at the desired rate. In this way, the chain reaction maintains a constant output of energy at a controlled rate.

All this takes place within the reactor core and is the first step in the electricity-generating process of a nuclear power plant (FIGURE 20.5). The reactor core is housed within a reactor vessel; and the vessel, steam generator, and associated plumbing loops are often protected within a containment building. Containment buildings, with their meter-thick concrete and steel walls, are constructed to prevent leaks of radioactivity due to accidents or natural catastrophes such as earthquakes. Not all nations require containment buildings, which points out the key role that government regulation plays in protecting public safety.

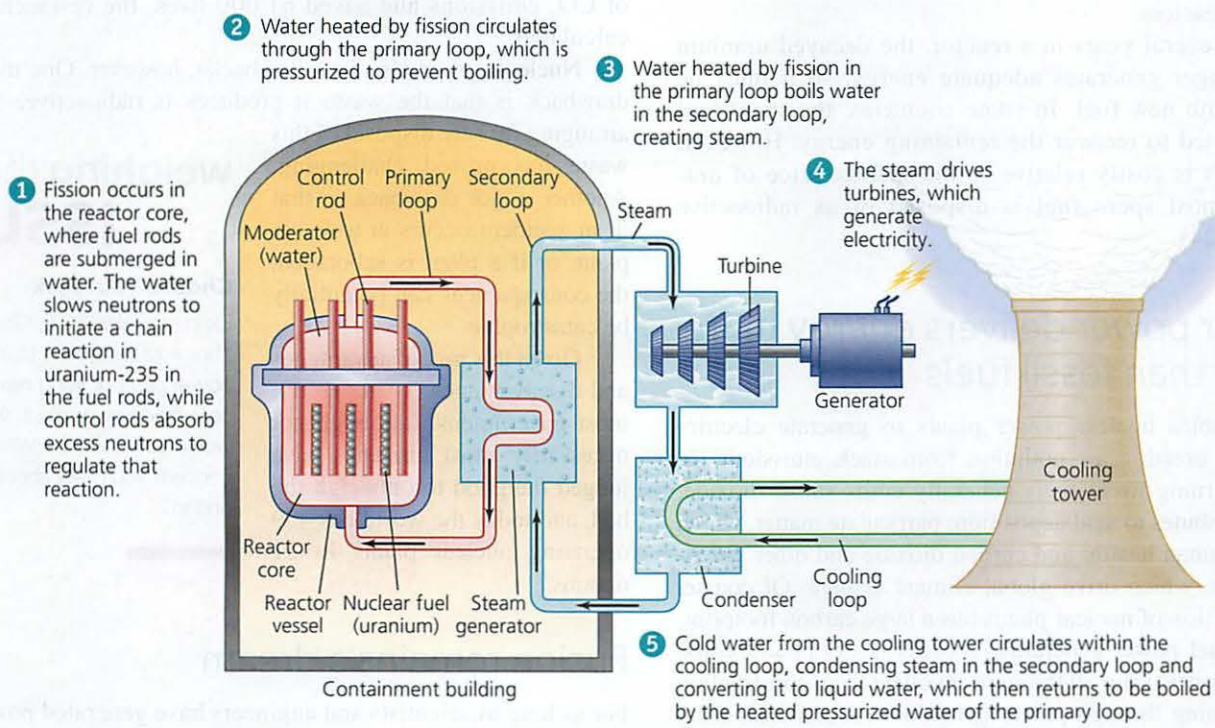


FIGURE 20.5 Nuclear reactors produce electricity. In a pressurized light water reactor (the most common type of nuclear reactor), uranium fuel rods are placed in water, which slows neutrons so that fission can occur 1. Control rods are moved into and out of the reactor core, absorbing excess neutrons to regulate the chain reaction. Water heated by fission circulates through the primary loop 2 and warms water in the secondary loop, where water turns to steam 3. Steam drives turbines, which generate electricity 4. The steam is cooled afterward in the cooling tower by water from an adjacent river or lake and returns to the containment building 5, to be heated again by heat from the primary loop.

Nuclear energy comes from processed and enriched uranium

We use the element uranium for nuclear power because it is radioactive. Radioactive isotopes, or radioisotopes (p. 24), emit subatomic particles and high-energy radiation as they decay into lighter radioisotopes until they ultimately become stable isotopes. The isotope uranium-235 decays into a series of daughter isotopes, eventually forming lead-207. Each radioisotope decays at a rate determined by that isotope's *half-life* (p. 24), the time it takes for half of the atoms to give off radiation and decay. The half-life of ^{235}U is about 700 million years.

We obtain uranium from various minerals in naturally occurring ore (rock that contains minerals of economic interest [p. 632]) that we extract by large-scale mining. Uranium-containing minerals are uncommon, and uranium ore is in finite supply, so nuclear power is generally considered a nonrenewable energy source. Currently, most uranium used in U.S. power plants is imported from abroad.

More than 99% of the uranium in nature occurs as the isotope uranium-238. Uranium-235 (with three fewer neutrons) makes up less than 1% of the total. Because ^{238}U does not emit enough neutrons to maintain a chain reaction when fissioned, we use ^{235}U for commercial nuclear power. Therefore, we must process the ore we mine to enrich the concentration of ^{235}U to at least 3%. The enriched uranium is formed into pellets of uranium dioxide (UO_2), which are incorporated into metallic tubes called *fuel rods* that are used in nuclear reactors.

After several years in a reactor, the decayed uranium fuel no longer generates adequate energy, so it must be replaced with new fuel. In some countries, the spent fuel is reprocessed to recover the remaining energy. However, this process is costly relative to the market price of uranium, so most spent fuel is disposed of as radioactive waste (p. 624).

Nuclear power delivers energy more cleanly than fossil fuels

Fission enables nuclear power plants to generate electricity without creating air pollution from stack emissions. In contrast, burning fossil fuels generally emits sulfur dioxide, which contributes to acid deposition; particulate matter, which threatens human health; and carbon dioxide and other greenhouse gases, which drive global climate change. Of course, the construction of nuclear plants has a large carbon footprint, but the actual power-generating process is essentially emission-free. Considering all the steps involved from construction through mining through power generation, researchers from the International Atomic Energy Agency (IAEA) have calculated that nuclear power releases from 4 to 150 times fewer emissions than fossil fuel combustion. Scientists estimate that nuclear power helps the United States avoid emitting 600 million metric tons of carbon dioxide each year, equivalent to the CO_2 emissions of almost all passenger cars in the nation and 11% of total U.S. CO_2 emissions. Globally, using nuclear power in place of fossil fuels helps the world avoid emissions of 2.5 billion metric tons of carbon dioxide per year, about 7% of global CO_2 emissions.

Nuclear power has additional advantages over fossil fuels—coal in particular. For residents living downwind from power plants, scientists calculate that nuclear power poses far fewer chronic health risks from pollution. For instance, nuclear power prevents the emission of half a million tons of nitrogen oxide and 1.4 million tons of sulfur dioxide each year that might otherwise be generated by coal-fired power plants. And because uranium generates far more power than coal by weight or volume, less of it needs to be mined. As a result, uranium mining causes less damage to landscapes and generates less solid waste than coal mining. Moreover, in the course of normal operation, nuclear power plants have proved safer for workers than coal-fired plants.

Supporting the assessment that nuclear power is safer in many ways than fossil fuel power, a 2015 research paper published in the journal *Energy Policy* examined Sweden's plan to phase out nuclear power, and calculated the costs that this would have if the nation had to replace the lost power with coal-fired power. These scientists concluded that replacing Sweden's nuclear plants with coal would produce 1.8 billion tons of extra carbon dioxide emissions and cause more than 51,000 extra deaths due to the health impacts of coal pollution. Already Sweden's nuclear plants, by replacing coal, had prevented 2.1 billion tons of CO_2 emissions and saved 61,000 lives, the researchers calculated.

Nuclear power also has drawbacks, however. One main drawback is that the waste it produces is radioactive, and arranging for safe disposal of this waste has proved challenging. Another major drawback is that if an accident occurs at a power plant, or if a plant is sabotaged, the consequences can potentially be catastrophic.

Given this mix of advantages and disadvantages (**TABLE 20.2**), most governments (although not necessarily most citizens) have judged the good to outweigh the bad, and today the world has 439 operating nuclear plants in 31 nations.

weighing the ISSUES

Choose Your Risk

Examine Table 20.2. Given the choice of living next to a nuclear power plant or living next to a coal-fired power plant, which would you choose? What would concern you most about each option?

Fusion remains a dream

For as long as scientists and engineers have generated power from nuclear fission, they have tried to figure out how to harness nuclear fusion as well. **Nuclear fusion**—the process that drives our sun's vast output of energy, and the force behind hydrogen bombs (thermonuclear bombs)—involves forcing together the small nuclei of lightweight elements under extremely high temperature and pressure.

TABLE 20.2 Risks and Impacts of Coal-Fired versus Nuclear Power Plants

TYPE OF IMPACT	COAL	NUCLEAR
Land and ecosystem disturbance from mining	Extensive, on surface or underground	Less extensive
Greenhouse gas emissions	Considerable emissions	None from plant operation; much less than coal over the entire life-cycle
Other air pollutants	Sulfur dioxide, nitrogen oxides, particulate matter, and other pollutants	No pollutant emissions
Radioactive emissions	No appreciable emissions	No appreciable emissions during normal operation; possibility of emissions during severe accident
Occupational health among workers	More known health problems and fatalities	Fewer known health problems and fatalities
Health impacts on nearby residents	Air pollution impairs health	No appreciable known health impacts under normal operation
Effects of accident or sabotage	No widespread effects	Potentially catastrophic widespread effects
Solid waste	More generated	Less generated
Radioactive waste	None	Radioactive waste generated
Fuel supplies remaining	Should last several hundred more years	Uncertain; supplies could last longer or shorter than coal supplies

For each type of impact, the more severe impact is highlighted in red.

The hydrogen isotopes deuterium and tritium can be fused together to create helium, releasing a neutron and a tremendous amount of energy (FIGURE 20.6).

Overcoming the mutually repulsive forces of protons in a controlled manner is difficult, however, and fusion requires temperatures of many millions of degrees Celsius. As a result, researchers have not yet developed this process for commercial power generation. Despite billions of dollars of funding and decades of research, fusion experiments in the lab still require scientists to input more energy than they produce from the process. That is, they experience a loss in net energy (p. 519) and a ratio of energy returned on investment (EROI; p. 520) lower than 1.

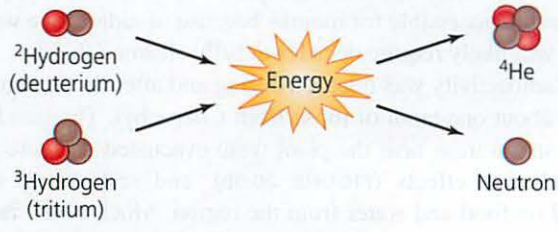


FIGURE 20.6 Can we harness nuclear fusion? In nuclear fusion, two small atoms, such as the hydrogen isotopes deuterium and tritium, are fused together, releasing energy along with a helium nucleus and a free neutron. So far, scientists have not been able to fuse atoms without supplying far more energy than the reaction produces, so this process is not used commercially.

If we could find a way to control fusion in a reactor, the potential payoffs would be immense. We could produce vast amounts of energy using water as a fuel, and the process would create only low-level radioactive wastes, without pollutant emissions or the risk of dangerous accidents, sabotage, or weapons proliferation. A consortium of industrialized nations is collaborating to build a prototype fusion reactor called the International Thermonuclear Experimental Reactor (ITER) in southern France. It aims to achieve an EROI of 10:1. Construction is scheduled for completion in 2019, and experiments would be conducted during the 2020s. Even if this multi-billion-dollar effort succeeds, however, commercial power from fusion seems unlikely in the near future.

Nuclear power poses small risks of large accidents

Although nuclear power delivers energy more cleanly than fossil fuels, the possibility of catastrophic accidents has spawned a great deal of public anxiety. Three events have been most influential in shaping public opinion about nuclear power: Three Mile Island, Chernobyl, and Fukushima.

Three Mile Island In Pennsylvania in 1979 a combination of mechanical failure and human error at the **Three Mile Island** plant caused coolant water to begin draining from the reactor vessel, temperatures to rise inside the reactor core, and metal surrounding the uranium fuel rods to start melting, releasing radiation. This process is termed a **meltdown,** and

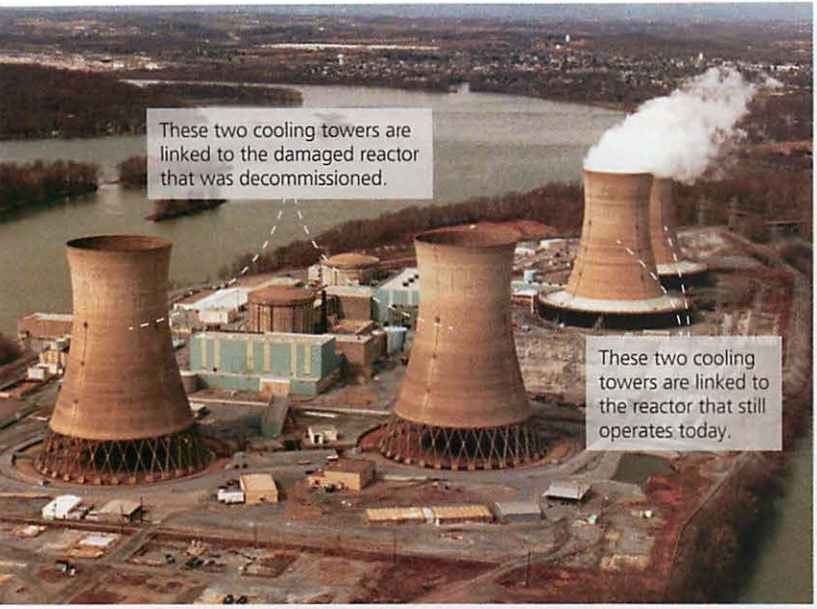


FIGURE 20.7 Pennsylvania's Three Mile Island nuclear power plant suffered a partial meltdown in 1979. This "near miss" alerted the world that a major accident could potentially occur.

at Three Mile Island (FIGURE 20.7) it proceeded through half of one reactor core. Residents of Harrisburg and nearby towns stood ready to be evacuated as the nation held its breath, but fortunately most radiation remained trapped inside the containment building.

The accident was brought under control within days, and the damaged reactor was shut down, but multi-billion-dollar cleanup efforts stretched on for years. Three Mile Island is best regarded as a near miss; the emergency could have been far worse had the meltdown proceeded through the entire stock of uranium fuel or had the containment building not contained the radiation. Although residents have shown no significant health impacts in the years since, the event raised safety concerns in the United States and abroad. In fact, it was Three Mile Island that inspired Sweden's referendum in 1980 that resulted in its national vote for a phaseout of nuclear power.

Chernobyl In 1986 an explosion at the **Chernobyl** power plant in Ukraine (part of the Soviet Union at the time) caused the most severe nuclear accident the world has yet seen (FIGURE 20.8a). Engineers had turned off safety systems to conduct tests, and human error, along with unsafe reactor design, led to explosions that destroyed the reactor and sent clouds of radioactive debris billowing into the atmosphere. For 10 days radiation escaped from the plant while emergency crews risked their lives putting out fires (some later died from radiation exposure). Most residents of the area remained at home for these 10 days, exposed to high levels of radiation, before the Soviet government belatedly began evacuating more than 100,000 people.

The accident killed 31 people directly and sickened or caused cancer in thousands more. Exact numbers are uncertain because of inadequate data and the difficulty of determining long-term radiation effects (see THE SCIENCE BEHIND THE STORY, pp. 560–561). Health authorities estimate that most of the 6000-plus cases of thyroid cancer diagnosed in people who were children at the time resulted from radioactive iodine spread by the accident.

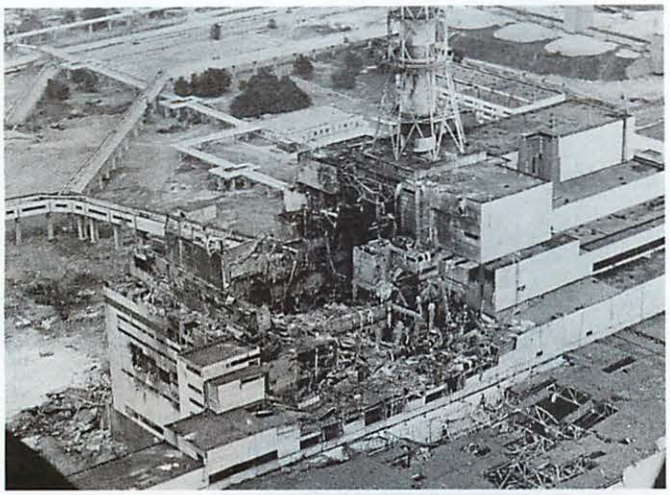
Atmospheric currents carried radioactive fallout from Chernobyl across much of the Northern Hemisphere, particularly Ukraine, Belarus, and parts of Russia and Europe (FIGURE 20.8b). Fallout was greatest where rainstorms brought radioisotopes down from the radioactive cloud. Parts of Sweden received high amounts of fallout, and the accident reinforced the Swedish public's anxieties about nuclear power. A poll taken after the event showed that nearly half of Swedish citizens had come to regret their own nation's investment in nuclear power.

In the months and years following the catastrophe at Chernobyl, workers erected a gigantic concrete sarcophagus around the demolished reactor and took measures to limit radioactive contamination of milk, meat, and produce from the region's farms. However, the landscape for at least 30 km (19 mi) around the plant remains contaminated today, the demolished reactor is still full of dangerous fuel and debris, and radiation is leaking from the hastily built, quickly deteriorating sarcophagus. Currently an international team is building a larger confinement structure (FIGURE 20.8c) and plans to slide it into place around the old sarcophagus to prevent a re-release of radiation.

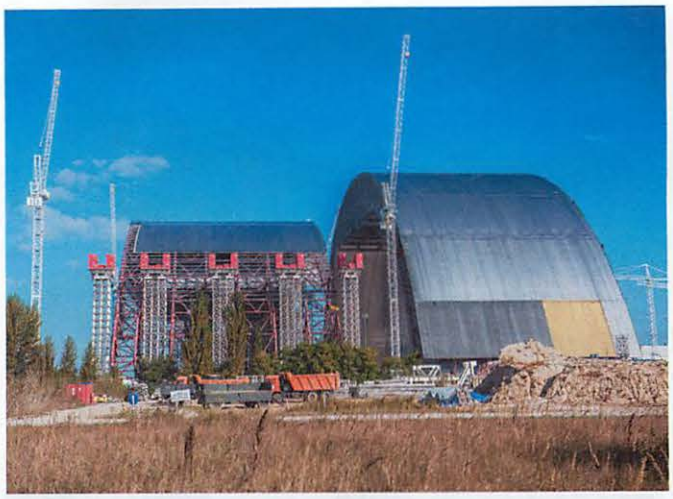
Fukushima Daiichi On March 11, 2011, a magnitude-9.0 earthquake struck eastern Japan and sent an immense tsunami roaring onshore (pp. 21–22). More than 18,000 people were killed, and many thousands of buildings were destroyed. This natural disaster also affected the operation of several of Japan's nuclear power plants, most notably **Fukushima Daiichi.** At this plant, the earthquake shut down power and the tsunami flooded the plant's emergency power generators. The plant was protected by a 5.7-m (19-ft) seawall, but the tsunami reached 14 m (46 ft) high, and the generators were located in the basement of the plant (FIGURE 20.9a, p. 558). Without electricity, workers could not use moderators and control rods to cool the uranium fuel, and the fuel began to overheat as fission proceeded, uncontrolled.

Amid the damage and chaos across the region, help was slow to arrive, so workers began flooding the reactors with seawater in a desperate effort to prevent meltdowns. Several explosions and fires occurred over the next few days, and eventually three reactors experienced full meltdowns, while the plant's other three reactors were seriously damaged. Parts of the plant remained inaccessible for months because of radioactive water, and it will likely require decades to fully clean up the site.

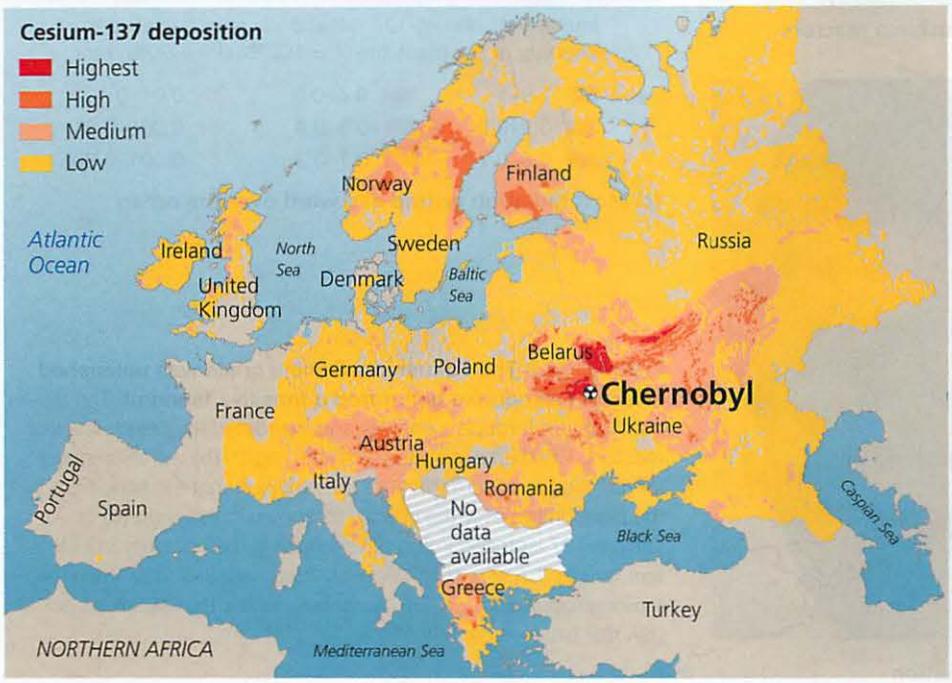
Radioactivity was released during and after these events at levels about one-tenth of those from Chernobyl. Thousands of residents of areas near the plant were evacuated and screened for radiation effects (FIGURE 20.9b), and restrictions were placed on food and water from the region. Much of the radiation spread by air or water into the Pacific Ocean, and trace amounts were detected around the world (FIGURE 20.9c). In the years following the event, a slow flow of radioactive groundwater from beneath the plant has continued to leak into the ocean. Long-term health effects on the region's people remain uncertain (see **The Science Behind the Story,** pp. 560–561).



(a) The destroyed reactor at Chernobyl, 1986



(c) The containment dome under construction, 2015



(b) The spread of radioactive fallout from Chernobyl, 1986

FIGURE 20.8 The world's worst nuclear accident unfolded in 1986 at Chernobyl. The destroyed reactor **(a)** was later encased in a massive concrete sarcophagus to contain further radiation leakage. Radioactive fallout **(b)** was deposited across Europe; complex patterns of cesium-137 deposition resulted from atmospheric currents and rainstorms in the days following the accident. Although Chernobyl produced 100 times more fallout than the U.S. bombs dropped on Hiroshima and Nagasaki in World War II, it was distributed over a much wider area. Thus, levels of contamination outside Ukraine, Belarus, and western Russia were relatively low. Today an international team is building a huge new confinement structure **(c)** that will be slid into place to encase the deteriorating sarcophagus around the plant. *Data from chernobyl.info, Swiss Agency for Development and Cooperation, Bern, Switzerland.*

In the aftermath of the disaster, Japan's government temporarily shut down all 50 of the nation's nuclear reactors and embarked on safety inspections. Afterward, efforts to restart them were met with public debate and street protests. Across the world, many nations responded by reassessing their own nuclear programs. In Sweden, where substantial majorities of citizens had long supported their nation's production of nuclear power, public opinion polls showed Swedes to be divided over whether to keep nuclear power or phase it out. Of all nations, Germany reacted most strongly, shutting down half of its nuclear power plants and deciding to phase out the rest by 2022. Sweden's environment minister at the time criticized Germany's decision, saying it would impede Germany's ability to move away from fossil fuels—and indeed, Germany has been burning more coal for power since that time. In 2015, Japan began restarting its nuclear plants, following four years of high electricity prices due to the import of replacement power fired by coal and natural gas. Yet despite the prospect of economic recovery, the majority of Japanese citizens remained opposed to restarting the nuclear plants.

We are managing risks from nuclear power and nuclear weapons with some success

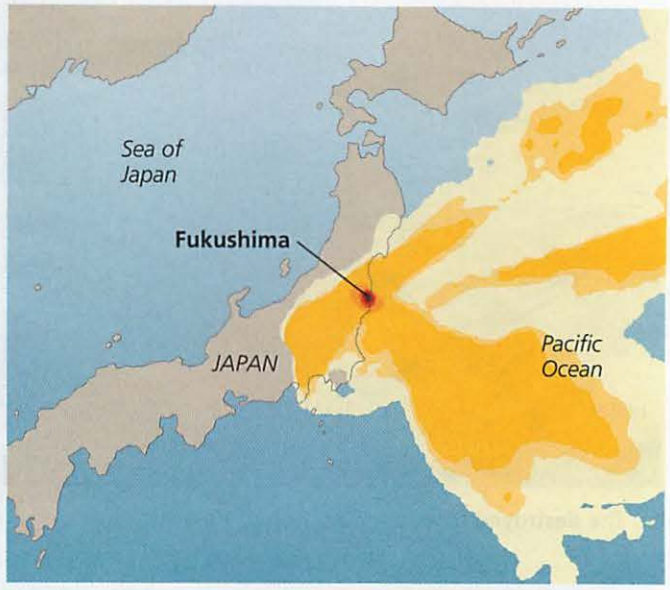
It is fortunate that we have not experienced more accidents on the scale of Fukushima or Chernobyl. Yet smaller-scale incidents have occurred. A 1999 accident at a plant in Tokaimura, Japan, killed two workers and exposed more than 400 others



(a) The tsunami barrels toward the Fukushima reactors



(b) A Japanese child is screened for radiation



(c) Most radiation drifted eastward over the ocean

FIGURE 20.9 The Fukushima Daiichi crisis was unleashed after an earthquake generated a massive tsunami. The tsunami **(a)** tore through a seawall and inundated the plant's nuclear reactors. Children evacuated from the region **(b)** were screened for radiation exposure. Most of the radiation that escaped from the plant drifted over the ocean, as shown in this map **(c)** of cesium-137 isotopes in the days following the accident. *Data (c) from Yasunari, T.J., et al. 2011. Cesium-137 deposition and contamination of Japanese soils due to the Fukushima nuclear accident.* Proc. Natl. Acad. Sci. USA *108: 19530–19534.*

to leaked radiation. Sweden experienced a near miss in 2006, when the Forsmark power plant north of Stockholm narrowly avoided a meltdown after two generators failed to start up following a power outage. Each year several U.S. reactors undergo emergency shutdowns in response to tornadoes, hurricanes, earthquakes, and flooding.

We can be thankful that the designs of most modern reactors are safer than Chernobyl's. Designs for future plants promise even more safety features. And in most emergencies at reactors around the world, safety systems have functioned well. For instance, Japan's Onagawa power plant was closer to the epicenter of the 2011 quake, yet its safety systems protected it from serious damage.

However, as plants around the world age, they require more maintenance and become less safe. There is also the concern that radioactive material could be stolen from plants and used in terrorist attacks. This possibility has been especially worrisome in the cash-strapped nations of the former Soviet Union, where hundreds of former nuclear sites have gone without adequate security for years. Finally, there is the ever-present concern that more nations may develop nuclear weapons.

To address concerns about stolen fuel and to reduce the world's nuclear weapons stockpiles, the United States and Russia embarked on a remarkably successful program nicknamed "Megatons to Megawatts." In this cooperative international agreement, the United States purchased weapons-grade uranium and plutonium from Russia, let Russia process them into lower-enriched fuel, and diverted the fuel to peaceful use in power generation. Between 1993 and 2013, 500 metric tons of highly enriched uranium were processed and transferred. As a result, in recent years fully 10% of America's electricity

has been generated from fuel recycled from Russian warheads that used to be atop missiles pointed at American cities!

Waste disposal remains a challenge

Even if nuclear power generation could be made completely safe, and even if we could recycle all weapons-grade fuel into fuel for power plants, we still would be left with the conundrum of what to do with spent fuel rods and other radioactive waste. Recall that fission uses ^{235}U as fuel, leaving as waste the 97% of uranium that is ^{238}U. This ^{238}U, as well as all irradiated material and equipment that is no longer being used, must be disposed of safely. The half-lives of uranium, plutonium, and many other radioisotopes are inconceivably long—700 million years for ^{235}U and 4.5 *billion* years for ^{238}U. As a result, this waste will continue emitting radiation for as long as our civilization exists. Thus, radioactive waste must be placed in unusually stable and secure locations where radioactivity will not harm future generations.

Currently, nuclear waste from power generation is being held in temporary storage at nuclear power plants across the world. Spent fuel rods are sunk in pools of cooling water to minimize radiation leakage (**FIGURE 20.10a**). However, many plants have no room left for this type of storage, so they are now storing waste in thick casks of steel, lead, and concrete (**FIGURE 20.10b**). In total, U.S. power plants are storing nearly 70,000 metric tons of high-level radioactive waste—enough to fill a football field to the depth of 7 m (21 ft)—as well as much more low-level radioactive waste. This waste is held at more than 120 sites spread across 39 states (**FIGURE 20.11**). The majority of Americans live within 125 km (75 mi) of temporarily stored waste.

Because storing waste at many dispersed sites creates a large number of potential hazards, nuclear waste managers would prefer to send all waste to a single, central repository that can be heavily guarded. Sweden is far ahead of most nations in this regard; after 20 years of research looking for a suitable location, it selected the Forsmark power plant site



(a) Wet storage



(b) Dry storage

FIGURE 20.10 Nuclear waste is stored at nuclear power plants, because no central repository yet exists. Spent fuel rods are kept in wet storage **(a)** in pools of water, which keep them cool and reduce radiation release, or in dry storage **(b)** in thick-walled casks layered with lead, concrete, and steel.

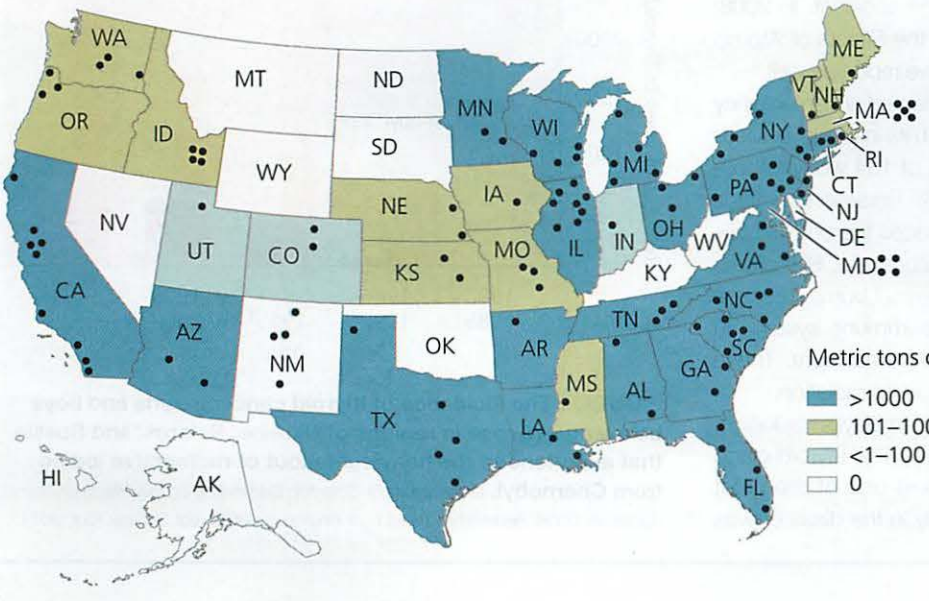


FIGURE 20.11 High-level radioactive waste from civilian reactors is currently stored at more than 120 sites in 39 states across the United States. In this map, dots indicate storage sites and colors indicate the amount of waste stored in each state. *Data from Nuclear Energy Institute.*

What Health Impacts Have Resulted from Chernobyl and Fukushima?



Chernobyl-area boy is tested for thyroid cancer in a Red Cross clinic.

In the wake of the meltdowns at Japan's Fukushima Daiichi nuclear power plant in 2011, Japanese authorities evacuated residents and tried to keep people safe, while medical scientists from around the world rushed to study how the release of radiation might affect human health. Both looked back to lessons learned from Chernobyl 25 years earlier.

Determining long-term health impacts of radiation exposure is enormously difficult, and initial attempts to predict Fukushima's health impacts have stirred vigorous debate. Most scientists expect that the reactor failures at Fukushima will have less severe health consequences than those at Chernobyl, because less radiation was emitted at Fukushima and because most of it drifted over the ocean away from populated areas (see Figure 20.9c and pp. 24–25). However, judging Fukushima's impacts will be challenging and will require long-term study.

Let's turn first to Chernobyl. The hundreds of researchers who have tried to pin down Chernobyl's health impacts have sometimes differed in their conclusions. In an effort to reach consensus, the World Health Organization (WHO) engaged 100 experts to review all studies through 2006 and issue a report summarizing what scientists had learned in the 20 years since the accident. In 2008, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) issued a comprehensive report as well.

The most severe effects were documented in emergency workers who battled to contain the incident in its initial days. Medical staff treated and recorded the progress of 134 workers hospitalized with acute radiation sickness (ARS). Radiation destroys cells in the body, and if the destruction outpaces the body's abilities to repair the damage, the person will soon die. Symptoms of ARS include vomiting, fever, diarrhea, thermal burns, mucous membrane damage, and weakening of the immune system. In total, 28 people died from ARS soon after the accident. Those who died had the greatest estimated exposure to radiation.

The major health consequence of Chernobyl's radiation, however, has been thyroid cancer in children. The thyroid gland is where our bodies concentrate iodine, and one of the most common radioactive isotopes released early in the disaster was iodine-131 (^{131}I). Healthy children have large and active thyroid glands, so they are especially vulnerable to thyroid cancer induced by radioisotopes.

Predicting that thyroid cancer might be a problem, medical workers measured iodine activity in the thyroid glands of several hundred thousand people in Russia, Ukraine, and Belarus following the accident. They also measured food contamination and surveyed people on their food consumption. These data showed that drinking milk from cows that had grazed on contaminated grass was the main route of exposure to ^{131}I, although fresh vegetables also contributed.

As doctors had feared, rates of thyroid cancer rose among children in regions of highest exposure (**FIGURE 1**). Multiple studies found linear dose-response relationships (p. 371) in data from Ukraine and Belarus. By 2006, medical professionals estimated the number of cases of thyroid cancer in children at 6000 and rising. Fortunately, treatment of thyroid cancer has a high success rate, so as of that time, only 15 children had died from it.

Studies addressing other health aspects of the accident have found limited impact. Some research has shown an increase in cataracts due to radiation, especially among emergency workers. But neither the WHO nor the United Nations assessments found evidence that rates of leukemia or any other cancer (aside from thyroid cancer) had risen among people exposed to Chernobyl's radiation. Still, some cancers may appear decades after exposure, so it is possible that many illnesses have yet to

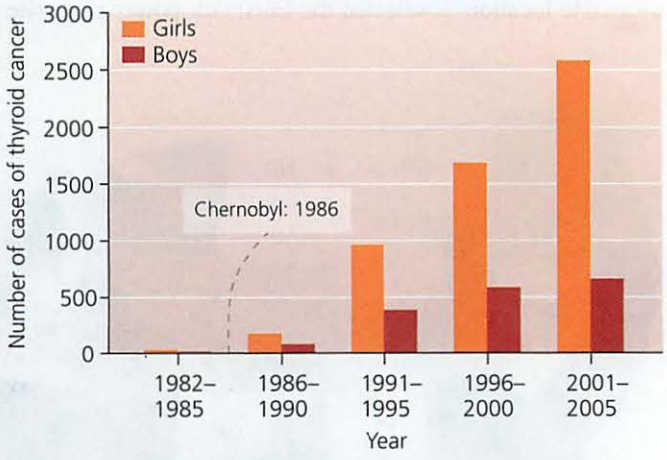


FIGURE 1 The incidence of thyroid cancer in girls and boys below age 18 rose in regions of Ukraine, Belarus, and Russia that experienced the heaviest fallout of radioactive iodine from Chernobyl. *Data from U.N. Scientific Committee on the Effects of Atomic Radiation, 2008.* Sources and effects of ionizing radiation, Vol. 2. *New York, 2011.*

arise. Moreover, conducting epidemiological studies (p. 370) with enough statistical power to detect minor increases in rare events requires observing huge numbers of people over many years.

When the Fukushima crisis struck, Japanese authorities applied lessons from Chernobyl. They provided iodine tablets to young people evacuated from the region (the tablets supply the thyroid gland with stable iodine, preventing it from taking up radioactive iodine). They also restricted agriculture near the plant, stopping contaminated food and milk from entering the market. These measures to prevent people's uptake of iodine-131 apparently were effective. In late March 2011, 1000 evacuated children were tested for ^{131}I exposure, and none showed evidence of a high dose affecting the thyroid.

As the crisis was gradually brought under control, some researchers began predicting what long-term health impacts might arise. Using data on cancer rates from studies on survivors of the atomic bombs dropped on Hiroshima and Nagasaki, researchers extrapolated to predict cancer rates at the lower radiation doses from Fukushima. Frank Von Hippel in a 2011 study calculated that about 1 million people were exposed to more than 1 curie per square kilometer of radiation from cesium-137, which should result in a 0.1% increase in cancer risk among them, or 1000 cancer cases.

In 2012, John Ten Hoeve and Mark Jacobson of Stanford University used a global atmospheric model together with data on radiation, population dispersion, and weather in the days following the event to estimate radiation levels people received (**FIGURE 2**). In the journal *Energy and Environmental Science*, they predicted that Fukushima's radiation would eventually produce 125 cancer-related deaths and 178 nonfatal cancer cases. Large uncertainties attended both estimates; the projected number of total cases ranged from 39 to 2900.

Meanwhile, their Stanford colleague Burton Richter wrote to the journal that—far from suggesting that nuclear power is dangerous—the number of fatalities from Fukushima is far less than Japan would have experienced from air pollution had its electricity been produced by fossil fuels instead!

As with Chernobyl, both the WHO and UNSCEAR issued status reports reviewing what was scientifically understood about health impacts from Fukushima in the years following the event. Both reports concluded that there was no evidence yet for any cancers or other health impacts, and that radiation levels were low enough that any increases in cancer risk were very small. Indeed, they cautioned that it will prove difficult to measure statistically rare instances of cancer in a large population exposed to very low doses.

Researchers will try, however. They will be assisted by Japan's government, which budgeted $1.2 billion for coordinated research into long-term health effects of radiation. Questionnaires were sent to all 2 million residents of Fukushima Prefecture, asking where they were in the days after the accident, and what they ate and drank. More than 500,000 of these surveys were returned. Thyroid exams are being given to all 360,000 children and teens from the region, and 20,000 pregnant women and their babies are being closely monitored. All 200,000 people evacuated from the area are getting regular exams, and mental health support is being offered. If this research program can extend for 30 years, as the government intends, it could provide valuable information on the health effects of low-dose radiation.

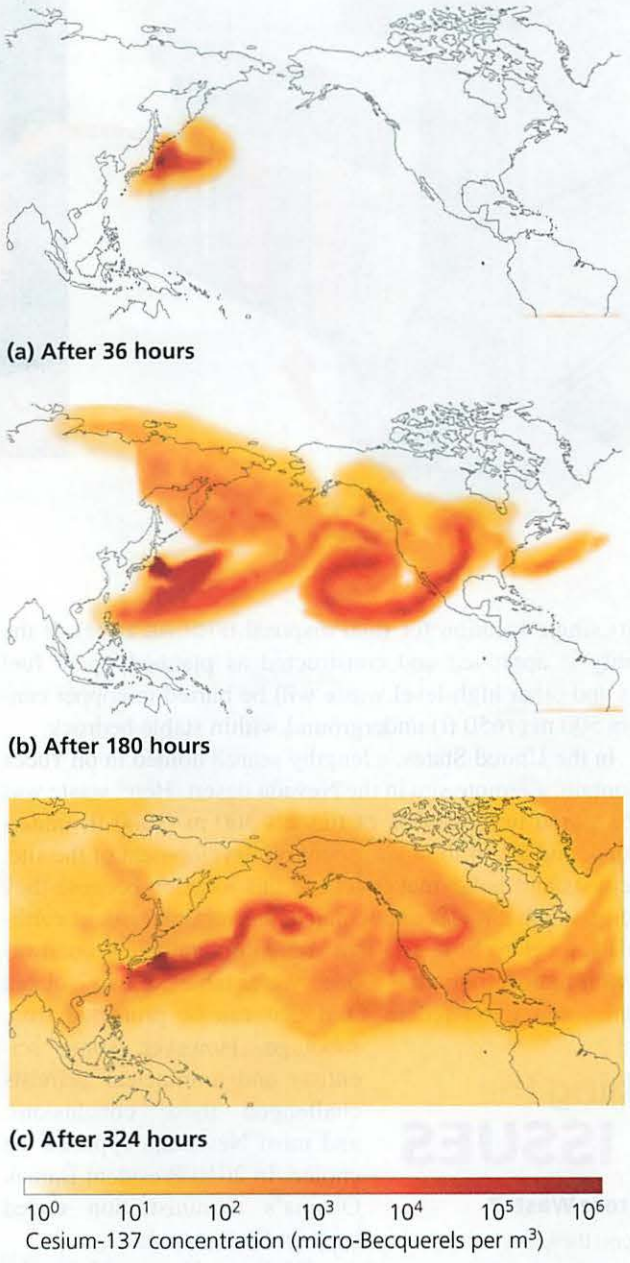


FIGURE 2 Radiation from cesium-137 spread around the world from Fukushima. Atmospheric modeling shows how this radioisotope spread for two weeks after the accident. *Data from Ten Hoeve, J., and M. Jacobson, 2012. Worldwide health effects of the Fukushima Daiichi nuclear accident.* Energy & Environmental Science *5: 8743–8757.*

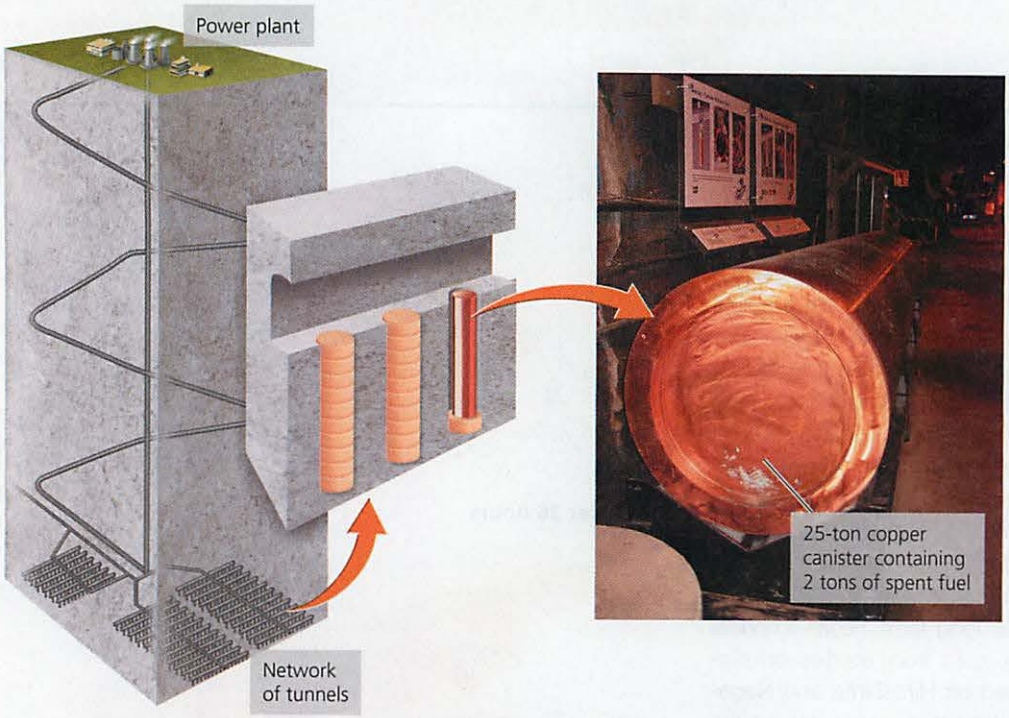


FIGURE 20.12 Sweden leads the world in attempts to establish a central repository for nuclear waste. Plans call for placing waste in copper canisters and burying them in a network of tunnels deep beneath the Forsmark nuclear power plant. Each canister will be surrounded by clay, and tunnels will be backfilled and sealed.

as its single location for final disposal (FIGURE 20.12). If the facility is approved and constructed as planned, spent fuel rods and other high-level waste will be buried in copper canisters 500 m (1650 ft) underground within stable bedrock.

In the United States, a lengthy search homed in on Yucca Mountain, a remote site in the Nevada desert. Here, waste was to be stored in a network of tunnels 300 m (1000 ft) underground, and $13 billion was spent on development of the site. Scientists and policymakers chose this location because they determined that it was unpopulated, has minimal risk of earthquakes, receives little rain that could contaminate groundwater with radioactivity, has a deep water table atop an isolated aquifer, and is on federal land that can be protected from sabotage. However, some scientists and antinuclear activists challenged these conclusions, and most Nevadans opposed the choice. In 2010 President Barack Obama's administration ended support for the project.

Without Yucca Mountain, the United States has no site designated to dispose of radioactive waste from commercial nuclear power plants. Until it does, this waste will remain spread among many locations.

Although storing nuclear waste at numerous widespread sites creates numerous risks, one concern with a centralized repository is that waste would need to be transported there from the many current storage sites and from each nuclear plant in the future. Because this would involve many thousands of shipments by rail and truck across hundreds of public highways through almost every state of the union, some people worry that the risk of an accident or of sabotage is unacceptably high.

weighing the ISSUES

How to Store Waste?

Which do you think is a better option—to transport nuclear waste cross-country to a single repository or to store it permanently at numerous power plants scattered across the nation? Would your opinion be affected if you lived near the repository site? Near a power plant? On a highway route along which waste is transported?

Nuclear power's growth has slowed

Dogged by concerns over waste disposal, safety, and cost overruns, nuclear power's growth has slowed. Since the late 1980s, nuclear power has grown by only 2.5% per year worldwide, about the same rate as electricity generation overall. Public anxiety in the wake of Chernobyl made utilities less willing to invest in new plants, and reaction to Fukushima stalled a resurgence in the industry. The process of building, maintaining, operating, and ensuring the safety of nuclear facilities is enormously expensive, and almost every nuclear plant has overrun its budget. In addition, plants have aged more quickly than expected because of problems that were underestimated, such as corrosion in coolant pipes. The plants that have been shut down—well over 100 to date—have served on average less than half their expected lifetimes. Moreover, shutting down, or decommissioning, a plant is sometimes more expensive than the original construction.

As a result of these financial issues, electricity from nuclear power remains more expensive than electricity from fossil fuels. Governments are still subsidizing nuclear power to keep electricity prices down for ratepayers, but many private investors lost interest long ago. In the United States, the nuclear industry stopped building plants following Three Mile Island, and public opposition scuttled many that were under construction. Of the 259 U.S. nuclear reactors ordered since 1957, nearly half have been canceled. At its peak in 1990, the United States had 112 operating reactors; in 2016 it had 99.

Nonetheless, nuclear power remains one of the few currently viable alternatives to fossil fuels with which we can generate large amounts of electricity in short order. This is why a growing number of environmental advocates propose expanding nuclear capacity using a new generation of reactors designed to be safer and less expensive. For a nation wishing to cut its pollution and greenhouse gas emissions quickly and substantially, nuclear power is in many respects the leading option.

With future growth for nuclear power uncertain, and with climate change worsening, our society must determine where we will turn for clean and sustainable energy. Increasingly, people are looking to renewable sources of energy: energy sources that are replenished naturally and cannot be depleted by our use. Many promising renewable sources are still early in their development (Chapter 21), but two of them—bioenergy and hydroelectric power—are already well developed and widely used. We will examine these renewable sources of energy next.

weighing the ISSUES

More Nuclear Power?

Sweden and a number of other European nations have reduced their carbon emissions by expanding their use of nuclear power to replace fossil fuels. Do you think the United States should expand its nuclear power program? Why or why not?

Bioenergy

Bioenergy—also known as *biomass energy*—is energy obtained from biomass. **Biomass** (p. 80) consists of organic material derived from living or recently living organisms, and it contains chemical energy (p. 28) that originated with sunlight and photosynthesis. We harness bioenergy from many types of plant matter, including wood from trees, charcoal from wood charred in the absence of oxygen, and matter from agricultural crops, as well as from combustible animal waste products such as cattle manure.

The great attraction of bioenergy is that—in principle—it is renewable and releases no net carbon dioxide into the atmosphere. Although burning biomass emits plenty of carbon, this is balanced by the fact that photosynthesis had pulled this same amount of carbon from the atmosphere to create the biomass just years, months, or weeks before. Therefore, in theory, when we replace fossil fuels with bioenergy, we reduce net carbon flux to the atmosphere, helping to alleviate global climate change (Chapter 18). However, in practice it is not so simple, and judging the sustainability of any given bioenergy strategy requires careful consideration of what biomass source we are using and how we gain energy from it.

We gain bioenergy from many sources

To a poor farmer in Africa, bioenergy comes from cutting wood from trees or collecting livestock manure by hand and burning it to heat and cook for her family. To an industrialized farmer in Iowa, bioenergy means shipping his grain to a hi-tech refinery that converts it to liquid fuel to run automobiles.

TABLE 20.3 Sources and Uses of Bioenergy

DIRECT COMBUSTION FOR HEATING
• Wood cut from trees (fuelwood)
• Charcoal
• Manure from farm animals
BIOPOWER FOR GENERATING ELECTRICITY
• Crop residues (such as cornstalks) burned at power plants
• Forestry residues (wood waste from logging) burned at power plants
• Processing wastes (solid or liquid waste from sawmills, pulp mills, and paper mills) burned at power plants
• "Landfill gas" burned at power plants
• Livestock waste from feedlots for gas from anaerobic digesters
BIOFUELS FOR POWERING VEHICLES
• Corn grown for ethanol
• Bagasse (sugarcane residue) grown for ethanol
• Soybeans, rapeseed, and other crops grown for biodiesel
• Used cooking oil for biodiesel
• Plant matter treated with enzymes to produce cellulosic ethanol
• Algae grown for biofuels

The diversity of sources and approaches involved in bioenergy (TABLE 20.3) gives us many ways to address our energy challenges.

More than 1 billion people use wood from trees as their principal energy source. In rural regions of developing nations, people (generally women) gather fuelwood to burn in their homes for heating, cooking, and lighting (FIGURE 20.13;



FIGURE 20.13 Well over a billion people in developing countries rely on wood from trees for heating and cooking. In principle, biomass is renewable, but in practice it may not be if forests are overharvested.

also see Figure 17.32, p. 472). Although fossil fuels and electricity are replacing traditional energy sources as developing nations industrialize, fuelwood, charcoal, and manure still account for one-third of energy use in these nations—and up to 90% in the poorest nations.

Fuelwood and other traditional biomass sources constitute three-quarters of all renewable energy used worldwide. However, biomass is renewable only if it is not overharvested. Harvesting fuelwood at unsustainably rapid rates can lead to deforestation (p. 305), soil erosion (p. 221), and desertification (p. 222), thereby damaging landscapes, diminishing biodiversity, and impoverishing societies. Heavily populated arid regions that support meager woodlands are most vulnerable to overharvesting, and these include many regions of Africa and Asia. Another drawback of burning fuelwood and other biomass for cooking and heating is that it poses health hazards from indoor air pollution (p. 472).

Although much of the world still relies on fuelwood, charcoal, and manure, new and innovative bioenergy approaches are being developed using a variety of materials (see Table 20.3). Some of these biomass sources can be burned in power plants to produce **biopower,** generating heat and electricity. Other sources can be converted into **biofuels,** liquid fuels used primarily to power automobiles. Because many of these novel biofuels and biopower strategies depend on technologies resulting from extensive research and development, they are being developed primarily in wealthier industrialized nations, such as Sweden and the United States.

We use biomass to generate electricity

We harness biopower by combusting biomass to produce heat or generate electricity in the same way that we burn coal for power (see Figure 19.11, p. 527). This can be done using a variety of sources and techniques.

Waste products Some waste products can be used as sources for biopower. The forest products industry generates large amounts of woody debris in logging operations (FIGURE 20.14) and at sawmills, pulp mills, and paper mills. Sweden's efforts to promote bioenergy have focused largely on using forestry residues. Because so much of the nation is forested and the timber industry is a major part of the Swedish economy, plenty of forestry waste is available.

Other waste sources used for biopower include animal waste from feedlots and residue from agricultural crops, such as cornstalks and corn husks. In addition, the anaerobic bacterial breakdown of waste in landfills produces methane, and this "landfill gas" is being captured and sold as fuel (p. 617). Methane and other gases can also be produced in a controlled way in anaerobic digestion facilities. This *biogas* can then be burned in a power plant's boiler to generate electricity.

The Swedish city of Kristianstad showcases just how much can be done with biogas. Back in 1999, this city of



FIGURE 20.14 Forestry residues are a major source of material for biopower in some regions. Here a Swedish logging operation gathers woody residue.

81,000 people—the hub of an agricultural and food processing region and best known as the home of Absolut Vodka—aimed to free itself of fossil fuels. After building a power plant that used forestry waste, it constructed a facility to turn waste into biogas. The biogas plant takes in household garbage, crop waste, food industry waste, and manure and uses anaerobic digestion to turn all this into biogas (FIGURE 20.15). The city's landfill and wastewater treatment plant also collect methane, adding to the city's biogas supply. The biogas is burned to generate electricity and to heat homes by district heating. It is also refined and used to fuel hundreds of cars, trucks, and buses designed to run on biogas (see photo, p. 549). All in all, this waste-to-energy system replaces about 7% of the city's gasoline and diesel fuel per year, all of its district heating, and much of its electricity, while excess biogas is sold to neighboring communities. A by-product of biogas production is liquid bio-fertilizer, and nearly 100,000 tons per year are sold to area farms.

Bioenergy crops We are beginning to grow certain types of plants as crops to generate biopower. These include fast-growing grasses such as bamboo, fescue, and switchgrass, as well as trees such as specially bred willows and poplars. Many of these plants are also being grown to produce liquid biofuels.

Combustion strategies Power plants built to combust biomass operate like those fired by fossil fuels; combustion heats water, creating steam to turn turbines and generators,

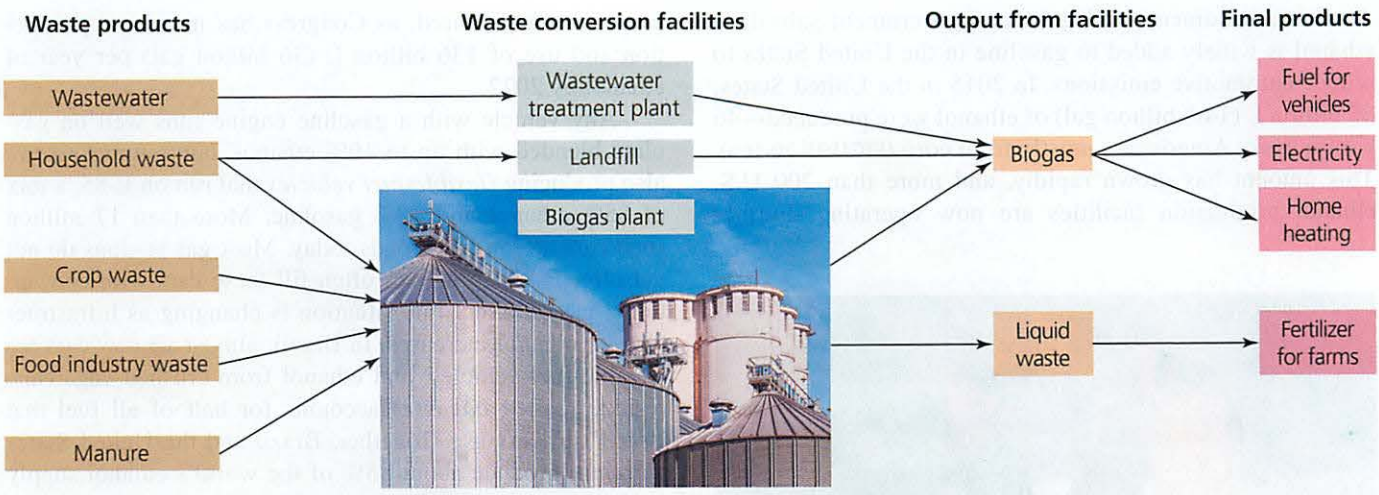


FIGURE 20.15 **In Kristianstad, Sweden, a diversity of waste products are converted into biogas, which provides vehicle fuel, electricity, and home heating.**

thereby generating electricity. Much of the biopower produced so far comes from power plants that use cogeneration (p. 542) to generate both electricity and heating. These plants are often located where they can take advantage of forestry waste.

In some coal-fired power plants, wood chips, wood pellets, or other biomass is introduced with coal into a high-efficiency boiler in a process called *co-firing*. We can substitute biomass for up to 15% of the coal with only minor equipment modification and no appreciable loss of efficiency. Co-firing is a relatively easy and inexpensive way for utilities to expand their use of renewable energy.

We also harness biopower by gasification (p. 538), in which biomass is vaporized at extremely high temperatures in the absence of oxygen, creating a gaseous mixture including hydrogen, carbon monoxide, carbon dioxide, and methane. This mixture can generate electricity when used to turn a gas turbine to propel a generator in a power plant. Another method of heating biomass in the absence of oxygen results in pyrolysis (p. 524), which produces a mix of solids, gases, and a liquid fuel called pyrolysis oil that can be burned to generate electricity.

Scales of production At small scales, farmers, ranchers, or villages can operate modular biopower systems that use livestock manure to generate electricity. Small household biodigesters provide portable and decentralized energy production for remote rural areas. At large scales, the forest products industry is using its waste to generate power, and industrialized farmers are growing bioenergy crops. In Sweden, nearly one-quarter of the nation's energy supply now comes from biomass, and biomass provides more than four times more fuel for electricity generation than coal, oil, and natural gas combined. Waste liquids from pulp mills, solid wood waste, municipal solid waste, biogas from digestion, and other sources are all used. In the United States, several dozen biomass-fueled power plants are now operating, and several dozen coal-fired plants are pursuing co-firing.

Benefits and drawbacks By enhancing energy efficiency and putting waste products to use, biopower helps move utilities and industries in a sustainable direction. The U.S. forest products industry now obtains half its energy by combusting woody waste and liquid waste from pulp mill processing. Biopower helps alleviate climate change as well by reducing carbon dioxide emissions, and capturing landfill gas reduces emissions of methane, a potent greenhouse gas. Biopower also benefits human health as it cuts down on pollution; by replacing coal in co-firing and direct combustion, biopower reduces emissions of sulfur dioxide because plant matter, unlike coal, contains no appreciable sulfur content. In addition, biomass resources tend to be geographically dispersed, so using them can help support rural economies and reduce many nations' dependence on imported fuels.

A disadvantage is that when we burn plant matter for power, we deprive the soil of nutrients and organic matter it would have gained from the plant matter's decomposition. We essentially draw fertility from the soil and never return it, so that the soil becomes progressively depleted. This also is the case when we burn crops or plant matter as a liquid fuel, as discussed next. The depletion of soil fertility is a major long-term problem for bioenergy and is one reason that relying solely on bioenergy is not a sustainable option.

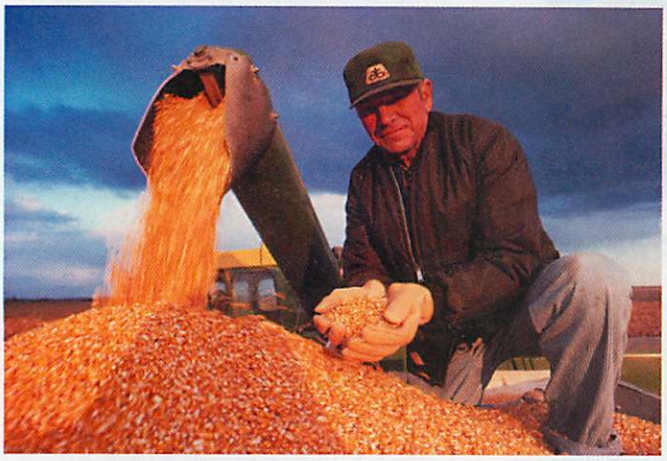
Ethanol can power automobiles

Liquid fuels from biomass sources are powering millions of vehicles on today's roads. The two primary biofuels developed so far are ethanol (for gasoline engines) and biodiesel (for diesel engines).

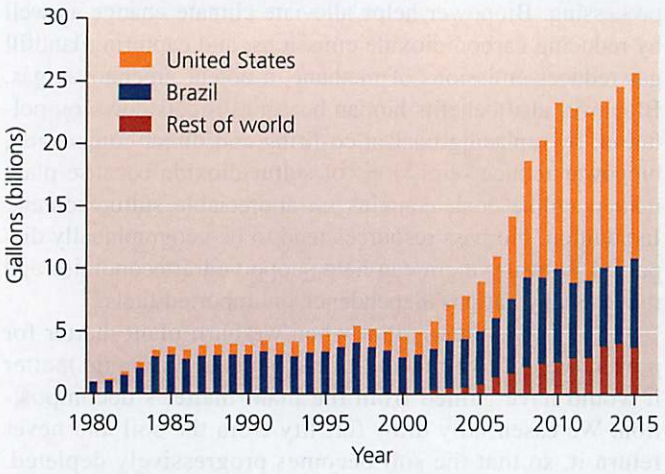
Ethanol is the alcohol in beer, wine, and liquor. It is produced as a biofuel by fermenting biomass, generally from carbohydrate-rich crops, in a process similar to brewing beer. In fermentation, carbohydrates are converted to sugars and then to ethanol. Spurred by the 1990 Clean

Air Act amendments and generous government subsidies, ethanol is widely added to gasoline in the United States to reduce automotive emissions. In 2015 in the United States, 56 billion L (14.8 billion gal) of ethanol were produced—46 gal for every American—mostly from corn (FIGURE 20.16a). This amount has grown rapidly, and more than 200 U.S. ethanol production facilities are now operating. Further growth seems assured, as Congress has mandated production and use of 136 billion L (36 billion gal) per year of ethanol by 2022.

Any vehicle with a gasoline engine runs well on gasoline blended with up to 10% ethanol, but automakers are also producing *flexible-fuel vehicles* that run on E-85, a mix of 85% ethanol and 15% gasoline. More than 17 million such cars are on U.S. roads today. Most gas stations do not yet offer E-85, so drivers often fill these cars with conventional gasoline, but this situation is changing as infrastructure for ethanol increases. In Brazil, almost all new cars are flexible-fuel vehicles, and ethanol from crushed sugarcane residue (called *bagasse*) accounts for half of all fuel that Brazil's drivers use. Together, Brazil and the United States currently produce about 85% of the world's ethanol supply (FIGURE 20.16b).



(a) Corn grown for ethanol



(b) Global ethanol production, 1980–2015

FIGURE 20.16 Ethanol is booming. About 40% of the U.S. corn crop **(a)** is used to produce ethanol to add to gasoline (28% after by-products are put to use). Next to the United States, Brazil produces most of the rest of the world's ethanol, from bagasse (sugarcane residue). Ethanol production **(b)** has grown rapidly in recent years. *Data (b) from EIA International Energy Statistics and Renewable Fuels Association.*

DATA Roughly what percentage of the world's ethanol is produced by the United States? Based on the data shown in the graph, give one explanation for why we might predict that U.S. and world ethanol production will be much higher in the future. Now explain one reason why we might predict that U.S. and world ethanol production will be about the same in the future as it is today.

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Ethanol is not our most sustainable energy choice

The enthusiasm for corn-based ethanol shown by U.S policymakers is not widely shared by scientists. Growing corn to produce ethanol intensifies pesticide use, fertilizer use, freshwater depletion, and other impacts of industrialized agriculture (p. 239). Fully 40% of the U.S. corn crop today is used to make ethanol. (Some by-products of ethanol production are used in livestock feed; with this accounted for, 28% of the U.S. corn crop goes solely toward ethanol.) Corn ethanol crops take up millions of acres of land. To produce all the automotive fuel used in the United States with ethanol from U.S. corn, the nation would need to expand its already immense corn acreage by more than four times (FIGURE 20.17). Even at our current level of production, ethanol already competes with food production and drives up food prices.

Growing corn for ethanol also requires substantial inputs of fossil fuel energy (for operating farm equipment, making petroleum-based pesticides and fertilizers, transporting corn to processing plants, and heating water in refineries to distill

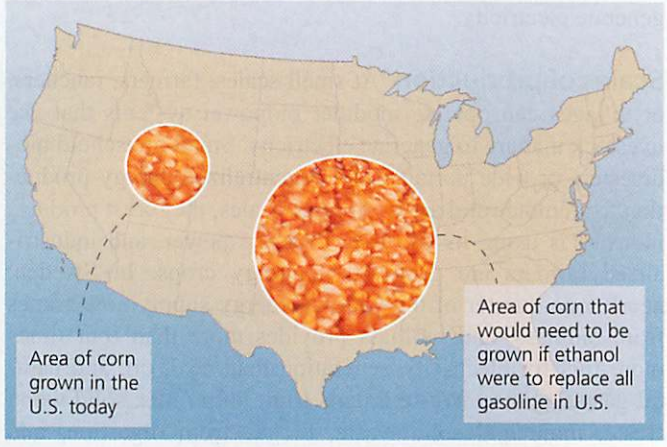


FIGURE 20.17 Growing corn to produce ethanol uses up a great deal of land. To produce enough ethanol to replace all gasoline used by U.S. drivers, the United States would need to more than quadruple its area planted in corn.

FAQ

If we substitute ethanol for gasoline, won't that solve our problems with oil dependence?

Increasing the proportion of ethanol in gasoline does indeed help to conserve oil and reduce reliance on foreign imports. However, obtaining the amount of corn ethanol needed to replace gasoline entirely would require that impractically large amounts of land be converted to corn production. Moreover, so much corn would likely be diverted from food to fuel that food prices would rise sharply. This is why researchers are studying other plants as more efficient sources of ethanol and are trying to produce cellulosic ethanol from crop and forestry wastes.

ethanol). Thus, simply shifting from gasoline to corn ethanol for our transportation needs would not eliminate our reliance on fossil fuels.

Moreover, corn ethanol yields only a modest amount of energy relative to the energy that needs to be input. The EROI ratio (p. 520) for corn-based ethanol is variable and controversial, but recent estimates place it around 1.3:1 (see **THE SCIENCE BEHIND THE STORY,** pp. 568–569). This means that to gain 1.3 units of energy from ethanol, we need to expend 1 unit of energy. The EROI of Brazilian bagasse ethanol is considerably higher, but the extremely low ratio for corn ethanol makes this fuel inefficient. For this reason, many critics do not view corn ethanol as an effective path to sustainable energy use.

Biodiesel powers diesel engines

Drivers of diesel-fueled vehicles can use **biodiesel,** a fuel produced from vegetable oil, used cooking grease, or animal fat. The oil or fat is mixed with small amounts of ethanol or methanol (wood alcohol) in the presence of a chemical catalyst. In Europe, where most biodiesel is used, rapeseed oil is the oil of choice, whereas U.S. biodiesel producers use mostly soybean oil. Vehicles with diesel engines can run on 100% biodiesel, or biodiesel can be mixed with conventional diesel derived from petroleum; a 20% biodiesel mix (called B20) is common today.

Replacing diesel with biodiesel cuts down on emissions (FIGURE 20.18). Biodiesel's fuel economy is nearly as good, it costs just slightly more, and it is nontoxic and biodegradable. Growing numbers of people are fueling their cars with biodiesel from waste oils. Indeed, some college students are creating biodiesel from food waste from dining halls and fast-food restaurants (FIGURE 20.19). Some buses and recycling trucks now run on biodiesel, and many state and federal fleets use biodiesel blends.

Some enthusiasts have taken biofuel use further. Eliminating the processing step that biodiesel requires, they use straight vegetable oil in their diesel engines (which requires modifying the engine).

Using waste oil as a biofuel is sustainable, but most biodiesel today, like most ethanol, comes from crops grown specifically for the purpose—and this has environmental impacts. Growing soybeans in Brazil and oil palms in Southeast Asia hastens the loss of tropical rainforest (pp. 306–308). Growing soybeans in the United States and rapeseed in Europe takes up large areas of land as well. Because the major crops grown

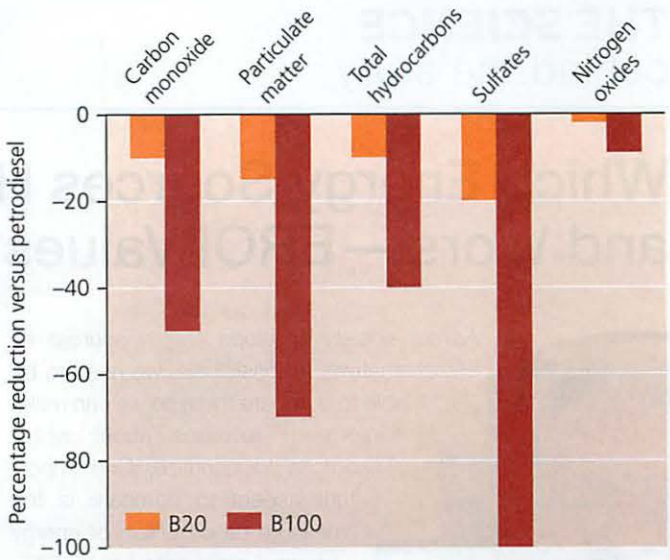


FIGURE 20.18 Burning biodiesel in a diesel engine emits less pollution than burning conventional petroleum-based diesel. Shown are percentage reductions in several major pollutants that one can attain by using B20 (a mix of 20% biodiesel and 80% petroleum-based diesel) and B100 (pure biodiesel). *Data from U.S. Environmental Protection Agency.*

DATA Which type of pollutant does use of biodiesel reduce most effectively, relative to petroleum-based diesel?

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for biodiesel and for ethanol exert heavy impacts on the land, farmers and agricultural scientists are experimenting with a variety of other crops, from wheat, sorghum, cassava, and sugar beets to lesser known plants such as hemp, jatropha, and the grass miscanthus.



FIGURE 20.19 At Loyola University Chicago, students and staff produce biodiesel from waste vegetable oil from the dining halls and use it to fuel this van. They transport this mini-diesel reactor to local high schools to teach students about alternative fuels.

Which Energy Sources Have the Best—and Worst—EROI Values?



Dr. Charles Hall, a pioneer of EROI research

As our society develops energy sources as alternatives to fossil fuels, we need to be able to compare them so we can make informed decisions about which sources to prioritize. One important aspect to compare is the measure called EROI, or energy returned on investment (p. 520), a ratio that indicates how much energy is produced for each unit of energy that is invested in the energy-producing activity.

It's fairly straightforward to measure how much energy is produced when we simply burn a fuel or when we let water or wind turn a turbine. The difficult part is calculating how much energy is invested across all the many and diverse aspects of finding, extracting, transporting, and using a resource, and in manufacturing the equipment needed to do so. To fully and accurately measure the denominator in an EROI ratio, the researcher must conduct a thorough life-cycle analysis (pp. 262, 618), summing up all the energy invested at each stage in the life-cycle of the process. Now that more researchers are beginning to do this, we are gaining better data that help us compare energy sources.

Charles Hall of the State University of New York (SUNY) College of Environmental Science and Forestry in Syracuse, New York, has been one of the pioneers in calculating EROI values. In 2014, he and students Jessica Lambert and Stephen Balogh surveyed recent research and compiled EROI estimates for major energy sources (**FIGURE 1**). Their summary, published in

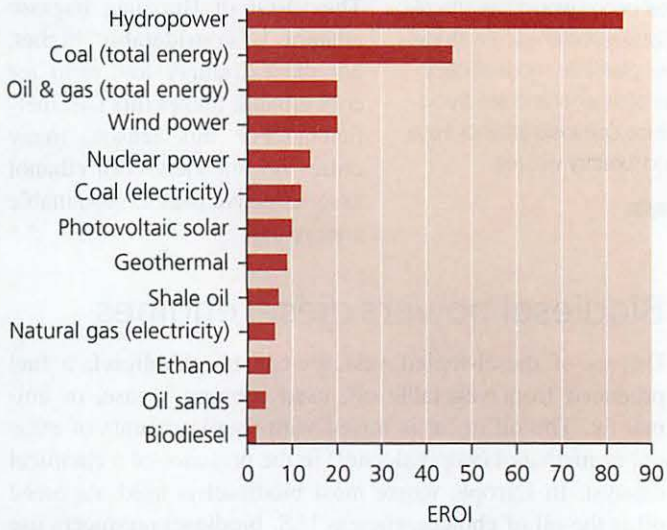


FIGURE 1 EROI ratios vary from more than 80:1 for hydropower down to 2:1 for biodiesel. *Adapted from Hall, C., et al. 2014. EROI of different fuels and the implications for society.* Energy Policy *64: 141–152.*



Novel biofuels are being developed

One promising next-generation biofuel crop is algae (better known to most of us as green pond scum!). Several species of these photosynthetic organisms produce large amounts of lipids that can be converted to biodiesel. Alternatively, carbohydrates in algae can be fermented to create ethanol. In fact, a variety of fuels, including jet fuel (**FIGURE 20.20**), can be produced from algae.

FIGURE 20.20 Commercial aircraft are beginning to use biofuels. KLM and several other European airlines have been powering flights with various biofuels for several years. United Airlines has used algae-based biofuel in a 30% blend on flights between Houston and Chicago since 2011. In 2015 it began fueling flights between Los Angeles and San Francisco with fuel derived from waste oils, farm waste, and landfill trash.

the journal *Energy Policy*, revealed a wide variation in the efficiency of our major energy sources.

Hydroelectric power had the best EROI value, averaging 84:1. This means that for each unit of energy we invest in hydropower, we produce 84 units of energy. This is because once dams, reservoirs, and transmission lines are constructed, passing running water through turbines year after year is highly efficient.

Nuclear power places above the middle of the pack in the Hall team's study, with an EROI of 14:1. Nuclear power produces a large amount of electricity, but it also requires substantial investment in uranium mining and in the facilities, equipment, and maintenance of power plants.

Solar power technologies tend to have moderately low EROI values, but as these young renewable technologies are further developed, we can expect EROI values to rise. Indeed, wind power is already among the most efficient energy sources, with an EROI around 20:1.

At the low end of the spectrum in the Hall team's study were biodiesel, oil sands, and ethanol, with EROIs of only 2:1, 4:1, and 5:1, respectively. Mining oil sands and processing their bitumen into usable oil requires huge amounts of energy expenditure (Chapter 19). The biofuels ethanol and biodiesel have low values because most come from crops like corn and soybeans grown in monocultures with industrial agriculture. Large amounts of equipment, fertilizer, pesticides, and irrigation—all powered by or made from fossil fuels—are used to grow these crops and then transport the yields to refineries.

Ethanol has received more research attention than any other fuel in regard to EROI, and results have varied. Early attempts at making cellulosic ethanol resulted in EROI values below 1:1 (energy was lost), whereas, in contrast, one study showed an EROI of 48:1 for ethanol from molasses in India. Earlier work by Hall found EROI values of ethanol from Brazilian sugarcane to average 5:1 but those from U.S. corn ethanol to average only 1.3:1. In fact, researchers have invariably found the EROI of corn ethanol to be remarkably low, and this is a large part of the reason many environmental scientists oppose U.S. government subsidies for corn ethanol.

In one 2011 research paper, Hall, Bruce Dale, and David Pimentel sought to clarify why different studies had come up with different EROI estimates for corn ethanol. By carefully comparing the methods of each study, they determined that the differences were due to how the researchers measured energy investment in the many steps involved in producing ethanol. They recommended that future researchers be more transparent and explicit about their methods as they try to work out the EROI values of newer biofuels, such as those from switchgrass and cellulosic ethanol.

The 2014 review by Hall and his students made clear that EROI values for fossil fuels were historically very high but have been dropping through the years (see Figure 19.6, p. 520). This is because we have already extracted the easy deposits and now need to expend more and more energy to reach the less-accessible deposits that remain. Newer, unconventional, fossil fuel resources such as oil sands and shale oil have low EROI values. This means that if we switch to these sources as conventional oil begins to run out, we will deplete them rapidly (while producing a great deal of pollution), because a great deal of energy will need to be devoted to extracting and processing them.

As studies of EROI become more numerous and higher in quality, they will help scientists, engineers, and policymakers compare the relative advantages of different energy sources. This will allow us to make better decisions as we chart our energy future and shift from fossil fuels to alternative and renewable energy sources.

Algae can be grown at a large scale in outdoor ponds, or more controlled and intensive production can be achieved in closed tanks or in closed transparent tubes called photobioreactors (**FIGURE 20.21**). Algae grow faster and produce more oil than terrestrial biofuel crops, and they can grow in seawater, saline water, or nutrient-rich wastewater from sewage treatment plants. Because carbon dioxide speeds their growth, algae can even make use of smokestack emissions. Indeed, placing algae farms next to power plants as a source of carbon capture (pp. 504, 538) is a promising combination. Producing biofuels from algae is expensive, but private investment may bring costs down.

Relying on any monocultural crop for energy may not be sustainable. With this in mind, researchers are refining techniques to produce **cellulosic ethanol** by using enzymes to produce ethanol from cellulose, the substance that gives structure to all plant material. This would be a major advance because ethanol as currently made from corn or sugarcane



FIGURE 20.21 Algae are a leading candidate for next-generation biofuels. Here algae grow at a demonstration facility.



FIGURE 20.22 Switchgrass is being studied as a crop to produce cellulosic ethanol, and also provides fuel for biopower.

uses starch, which is nutritionally valuable to us, and proponents of food security voice ethical concerns about using crops for fuel when millions of people continue to die from hunger. Cellulose, in contrast, is of no food value to people yet is abundant in all plants. If we can produce cellulosic ethanol in commercially feasible ways, then ethanol could be made from low-value crop waste (residues such as corn stalks and husks) rather than from high-value crops.

weighing the ISSUES

Biofuels

Do you think producing and using ethanol from corn is a good idea? Do the benefits outweigh the drawbacks? Explain why or why not. Do you think we should invest billions of dollars into developing next-generation biofuels such as algae and cellulosic ethanol? Can you suggest ways of using biofuels that would minimize environmental impacts?

Certain plants hold promise as crops specifically for cellulosic ethanol. Switchgrass (FIGURE 20.22) could potentially be a sustainable choice for the United States because it is a native grass of the North American prairies. It could provide wildlife habitat while serving as a crop, especially if planted in a polyculture mixed with other species. Cellulosic ethanol from switchgrass has an EROI ratio of 5:1 (much better than corn ethanol's), and growing this perennial grass could prevent the soil erosion and depletion of soil carbon that would result from removing too much crop waste for ethanol.

Is bioenergy carbon-neutral?

In principle, energy from biomass is carbon-neutral, releasing no net carbon into the atmosphere. This is because burning biomass releases carbon dioxide that plants recently pulled from the air by photosynthesis. However, burning biomass for energy is not carbon-neutral if forests are destroyed to plant bioenergy crops. Forests sequester more carbon (in vegetation and in soil) than croplands do, so cutting forests to plant crops will increase carbon flux to the atmosphere. Bioenergy also is not carbon-neutral if we consume fossil fuel energy to produce the biomass (for instance, by using tractors, fertilizers, and pesticides to grow biofuel crops).

International climate change policy so far has failed to encourage sustainable bioenergy approaches. The Kyoto Protocol (p. 506) required nations to submit data on emissions from energy use and from changes in land use, but only the emissions from energy use were "counted" toward judging how well nations were controlling their emissions under the treaty. Negotiators trying to design a follow-up treaty to Kyoto have been trying to address this (p. 507). In the meantime, researchers are trying to develop means of using bioenergy that are truly renewable and carbon-neutral. With continued research and careful decision making, our many bioenergy options may provide promising avenues for sustainably replacing fossil fuels.

Hydroelectric Power

Next to biomass, we draw more renewable energy from the motion of water than from any other resource. In **hydroelectric power,** or **hydropower,** we use the kinetic energy of flowing river water to turn turbines and generate electricity. We examined hydroelectric power and its environmental impacts in our discussion of freshwater resources (pp. 400–402). Now we will take a closer look at hydropower as an energy source.

Hydropower uses three approaches

Most hydroelectric power today comes from impounding water in reservoirs behind concrete dams that block the flow of river water and then letting that water pass through the dam. Because water is stored behind dams, this is called the **storage** technique. As reservoir water passes through a dam, it turns the blades of turbines, which cause a generator to generate electricity (FIGURE 20.23). Electricity generated in the powerhouse of a dam is transmitted by transmission lines to the electrical grid that serves consumers, while the water flows to the riverbed below the dam and continues downriver. The amount of power generated depends on the distance the water falls and the volume of water released. By storing water in reservoirs, dam operators can ensure a steady and predictable supply of electricity, even during periods of naturally low river flow.

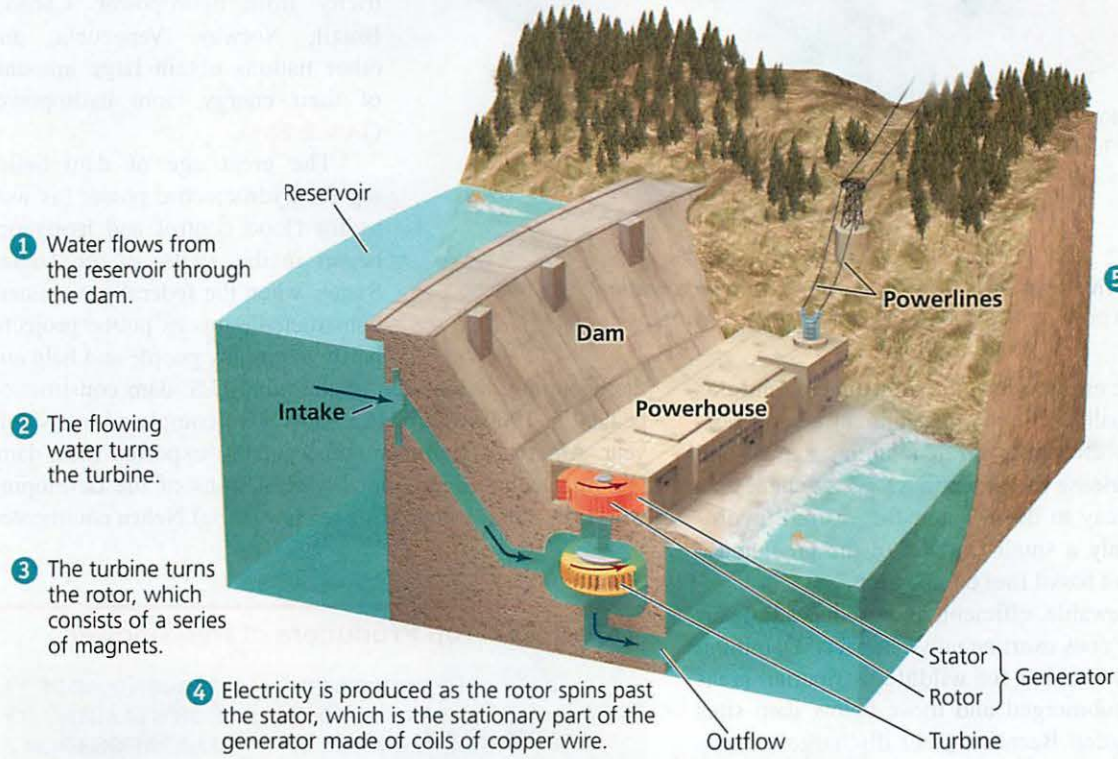
An alternative approach is the **run-of-river** technique, which generates electricity without greatly disrupting a river's flow. One method is to divert a portion of a river's flow through a pipe or channel, passing it through a powerhouse and then returning it to the river (FIGURE 20.24, p. 572). This can be done with or without a small reservoir that pools water temporarily, and the pipe or channel can be run along the surface or underground. Another method is to flow river water over a dam small enough not to impede fish passage, siphoning off water to turn turbines, and then returning the water to the river. Run-of-river systems are useful in areas remote from established electrical grids and in regions without the economic resources to build and maintain large dams. This approach cannot guarantee reliable water flow in all seasons, but it minimizes many impacts of the storage technique.



(a) Ice Harbor Dam, Snake River, Washington



(b) Generators inside McNary Dam, Columbia River



(c) Hydroelectric power

FIGURE 20.23 We generate hydroelectric power with large dams. Inside these dams **(a)**, flowing water turns massive turbines, which rotate generators **(b)** to generate electricity. Water is funneled from the reservoir through the dam **(c)** to rotate turbines, which turn rotors containing magnets. The spinning rotors generate electricity as their magnets pass coils of copper wire. Electrical current is transmitted through power lines, and the river's water flows out through the base of the dam.

To better control the timing of flow, pumped-storage hydropower can be used. In **pumped storage,** water is pumped from a lower reservoir to a higher reservoir during times when demand for power is weak and prices are low. When demand is strong and prices are high, water is allowed to flow downhill through a turbine, generating electricity. Although energy must be input to pump the water, pumped storage can be profitable. When paired with intermittent sources such as solar and wind power, it can help balance a region's power supply by compensating for dips in power.

Hydropower is clean and renewable, yet has impacts

Hydroelectric power has three clear advantages over fossil fuels. First, it is renewable; as long as precipitation falls from the sky and fills rivers and reservoirs, we can use water to turn turbines. Second, hydropower is efficient. It is thought to have an EROI ratio of more than 80:1, higher than any other modern energy source. Third, no carbon compounds are burned in the production of hydropower, so no carbon dioxide

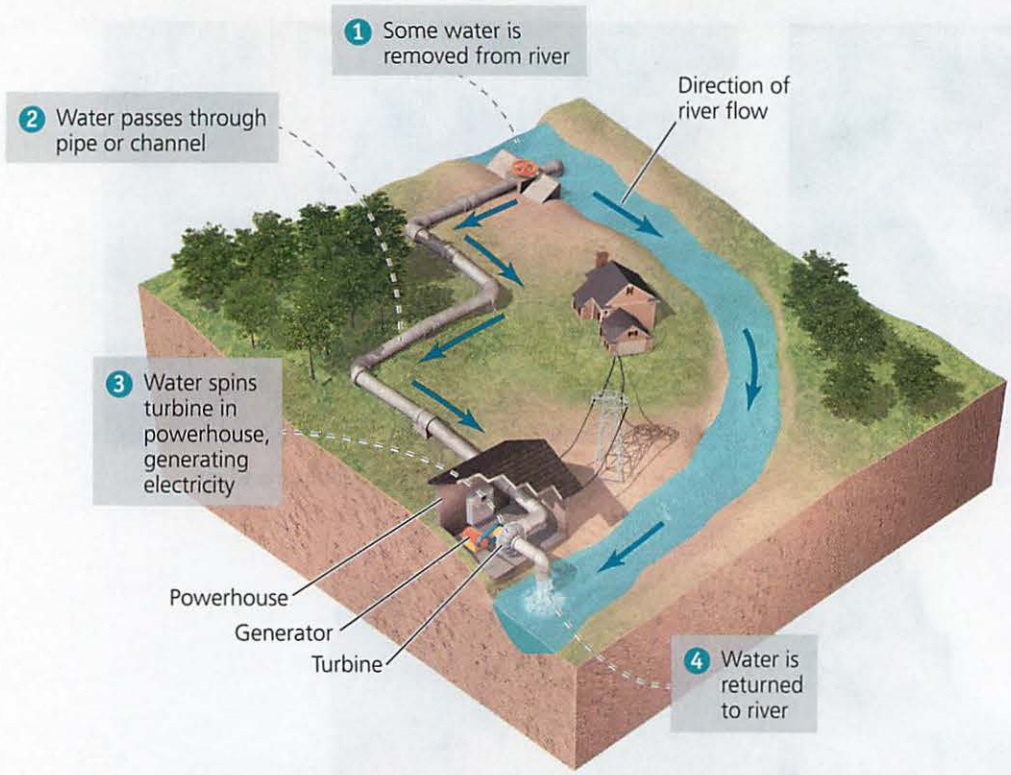


FIGURE 20.24 Run-of-river systems divert a portion of a river's water. Water may be piped downhill through a powerhouse and released downriver, as shown.

Hydroelectric power is widely used, but it may not expand much more

Hydropower accounts for one-sixth of the world's electricity production (see Figure 20.2b). For nations with large amounts of river water and the economic resources to build dams, hydroelectric power has been a keystone of their development and wealth. Sweden receives 11% of its total energy and nearly half its electricity from hydropower. Canada, Brazil, Norway, Venezuela, and other nations obtain large amounts of their energy from hydropower (TABLE 20.4).

The great age of dam building for hydroelectric power (as well as for flood control and irrigation) began in the 1930s in the United States, when the federal government constructed dams as public projects, partly to employ people and help end the economic depression of the time. U.S. dam construction peaked in 1960, when 3123 dams were completed in a single year. American engineers subsequently exported their dam-building technologies, notably to nations of the developing world. In India, Prime Minister Jawaharlal Nehru commented

or other pollutants are emitted into the atmosphere, and this helps safeguard air quality, climate, and human health. Fossil fuels *are* used in constructing and maintaining dams—and large reservoirs may release the greenhouse gas methane as a result of anaerobic decay in deep water. But overall, hydropower accounts for only a small fraction of the greenhouse gas emissions typical of fossil fuel combustion.

Although it is renewable, efficient, and produces little air pollution, hydropower does exert negative impacts. Damming rivers (p. 400) destroys habitat for wildlife as riparian areas above dam sites are submerged and those below dam sites often are starved of water. Because water discharge is regulated to optimize electricity generation, the natural flooding cycles of rivers are disrupted. Suppression of flooding prevents river floodplains from receiving fresh nutrient-laden sediments. Instead, sediments become trapped behind dams, where they begin filling the reservoir. Dams also cause thermal pollution (p. 407), because water downstream may become unusually warm if water levels are kept unnaturally shallow. Moreover, periodic flushes of cold water occur from the release of reservoir water. Such thermal shocks, together with habitat alteration, have diminished or eliminated native fish populations in many dammed waterways. In addition, dams generally block the passage of fish and other aquatic creatures, effectively fragmenting the river and reducing biodiversity in each stretch.

All these ecological impacts generally translate into negative social and economic impacts on local communities. (We discussed the benefits, drawbacks, and impacts of dams more fully in Chapter 15; pp. 400–402.)

TABLE 20.4 Top Producers of Hydropower

NATION	HYDROPOWER PRODUCED (PERCENTAGE OF WORLD TOTAL)	PERCENTAGE OF NATION'S ELECTRICITY GENERATION FROM HYDROPOWER
China	23.8	16.9
Canada	10.1	60.1
Brazil	10.1	68.6
United States	7.5	6.7
Russia	4.7	17.3
India	3.7	11.9
Norway	3.3	96.1
Japan	2.2	8.1
Venezuela	2.2	67.8
France	2.0	13.2

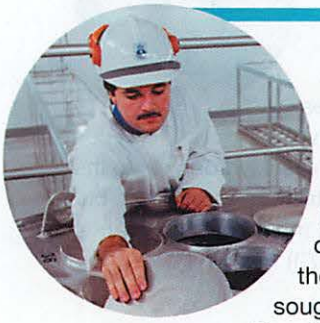
Data from the International Energy Agency.

in 1963 that "dams are the temples of modern India," referring to their central importance in the development of energy capacity in that nation.

Today the world is witnessing some gargantuan hydroelectric projects. China's recently completed Three Gorges Dam (p. 400) is the world's largest. Its reservoir displaced 1.3 million people, and the dam is now generating as much electricity as dozens of coal-fired or nuclear plants.

However, hydropower has less potential for expansion than most other renewable energy sources. The main reason is that most of the world's large rivers that offer excellent opportunities for hydropower are already dammed. For instance, in the wake of Sweden's 1980 referendum to phase out nuclear power, many Swedes had hoped that hydropower could compensate for the electrical capacity that would be lost. However, Sweden had already dammed so many of its rivers that it could not gain much additional hydropower by erecting more dams. In addition, as people have grown more aware of the ecological impacts of dams, residents in some regions are resisting dam construction. This is the case in Sweden, where many citizens have made it clear that they want some rivers to remain undammed, preserved in their natural state. As a result, in Sweden, hydropower's contribution to the national energy budget has remained little changed for 40 years. In the United States, 98% of rivers appropriate for dam construction already are dammed, many of the remaining 2% are protected under the Wild and Scenic Rivers Act, and efforts are underway to dismantle some existing dams and restore river habitats (p. 401).

Overall, hydroelectric power will likely continue to increase in developing nations that have yet to dam their rivers, but in developed nations hydropower growth will likely slow down. The International Energy Agency forecasts that hydropower's share of electricity generation will decline very slightly between now and 2035, whereas the share of other renewable energy sources will nearly triple. Newer renewable energy sources have impressive potential for rapid growth (Chapter 21).



closing THE LOOP

Given the considerable impacts of fossil fuel extraction and combustion on health, environmental quality, and the global climate, many nations have sought to diversify their energy portfolios with alternative energy sources. The three most developed and widely used alternatives to fossil fuels so far are nuclear power, bioenergy, and hydroelectric power.

Nuclear power showed promise to be a pollution-free and highly efficient form of energy. But escalating costs and public fears over safety in the wake of accidents at Three Mile Island, Chernobyl, and Fukushima stalled its growth, and a few nations are attempting to phase it out completely. Bioenergy sources are diverse and range from traditional fuelwood to newer biofuels and various means of generating biopower. These sources can be carbon-neutral but are not all strictly renewable. Hydropower is a renewable, pollution-free alternative, but it can expand only so much further and also involves substantial ecological impacts.

Some nations already use these three conventional alternatives extensively. Sweden has invested in them so greatly that it has managed to cut its fossil fuel use in half, and as we have learned, its government now aims to make Sweden the first nation in history to free itself of fossil fuels. Whether or not this goal is met, Sweden demonstrates that having a vibrant, healthy, and wealthy society does not in fact require a heavy reliance on fossil fuels. As Sweden navigates its ongoing societal debate over the safety of nuclear power, it can boast that it is already saving thousands of its citizens' lives each year by using far less coal, oil, or gas to generate its electricity. Regardless of the outcome of the debate over nuclear power, today Swedes—and growing numbers of people everywhere—are looking forward to a world powered by renewable energy.

REVIEWING Objectives

You should now be able to:

Discuss the reasons for seeking energy alternatives to fossil fuels

Fossil fuels are nonrenewable resources, and we are gradually depleting their easily accessible reserves. Burning fossil fuels causes air pollution that results in many environmental and health impacts and contributes to global climate change. (pp. 550–551)

Summarize the contributions to world energy supplies of conventional alternatives to fossil fuels

Alternatives to fossil fuels that are most widely used include nuclear power, bioenergy, and hydroelectric power. Biomass provides 10% of global primary energy use, nuclear power provides 5%, and hydropower provides 2%. Nuclear power generates 11% of the world's electricity, and hydropower generates 16%. (pp. 550–552)



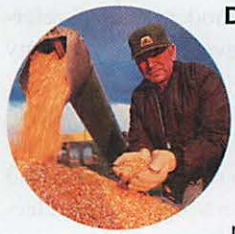
Describe nuclear energy and explain how we harness it for electrical power

We gain nuclear power by converting the energy of subatomic bonds into thermal energy, using uranium isotopes. Uranium is mined, enriched, processed into pellets and fuel rods, and used in nuclear reactors. By controlling the reaction rate of nuclear fission, nuclear power plant engineers produce heat that powers electricity generation. (pp. 552–554)



Assess the benefits and drawbacks of nuclear power, and discuss the societal debate over this energy source

Nuclear power is a clean energy source because it does not emit the pollutants that fossil fuels do. It thereby reduces health impacts and helps address climate change. However, for many people the risk of a catastrophic power plant accident, like those at Chernobyl and Fukushima, outweighs these benefits. The disposal of nuclear waste also remains a dilemma: Both temporary storage and single-repository approaches involve risks. Adding to these concerns, economic factors and cost overruns have slowed the nuclear industry's growth. (pp. 554–563)



Describe established and emerging sources and techniques involved in harnessing bioenergy, and assess bioenergy's benefits and shortcomings

Fuelwood remains the major source of bioenergy, especially in developing nations. We use biomass to generate electrical power in several ways with a variety of source materials. Biofuels such as ethanol and biodiesel are used to power automobiles; some crops are grown for this purpose, and waste oils are also used. Bioenergy is renewable and in principle adds no net carbon to the atmosphere, but overharvesting of wood can lead to deforestation, and growing crops solely for fuel can be inefficient and ecologically damaging. New biofuels from algae and cellulosic ethanol need further research and development but hold promise for more sustainable biofuel production. (pp. 563–570)



Outline the scale, methods, and impacts of hydroelectric power

Hydroelectric power is generated when water from a river runs through a powerhouse and turns turbines. Three major approaches (storage, run-of-river, and pumped storage) each offer advantages. Hydropower produces little air pollution, but dams and reservoirs alter riverine ecology and local economies. Hydropower is the world's largest source of electricity outside of fossil fuels, but its long-term growth potential appears more limited than that of other renewable sources. (pp. 570–573)

TESTING Your Comprehension

1. How much of our global energy supply do nuclear power, bioenergy, and hydroelectric power contribute? How much of our global electricity do these three conventional energy alternatives generate?
2. Describe how nuclear fission works. How do nuclear plant engineers control fission and prevent a runaway chain reaction?
3. In terms of greenhouse gas emissions, how does nuclear power compare to coal, oil, and natural gas? How do hydropower and bioenergy compare?
4. In what ways did the events at Three Mile Island, Chernobyl, and Fukushima Daiichi differ? What consequences resulted from each incident?
5. List several concerns about the disposal of radioactive waste. What has been done so far about its disposal?
6. List five sources of bioenergy. What is the world's most used source of bioenergy? How does bioenergy use differ between developed and developing nations?
7. Describe two biofuels, identify where each comes from, and explain how each is used.
8. Evaluate two potential benefits and two potential drawbacks of bioenergy.
9. Compare and contrast the three major approaches to generating hydroelectric power.
10. Assess two benefits and two negative environmental impacts of hydroelectric power.

SEEKING Solutions

1. Nuclear power has by now been widely used for a half-century, and the world has experienced only two major accidents (Chernobyl and Fukushima) responsible for any significant number of health impacts. Would you call this a good safety record? Should we maintain, decrease, or increase our reliance on nuclear power? Why might safety at nuclear power plants be better in the future? Why might it be worse?
2. How serious a problem do you think the disposal of radioactive waste represents? Describe in detail how you would like to see this issue addressed.

3. There are many different sources of biomass and many ways of harnessing energy from biomass. Discuss one that seems particularly beneficial to you, and one with which you see problems. What bioenergy sources and strategies do you think our society should focus on investing in?
4. **CASE STUDY CONNECTION** Sweden's prime minister has appointed you as the nation's energy minister, and has asked you to recommend and direct energy policies for Sweden. Based on everything you have learned from this chapter, describe how you would approach the question of whether or not to phase out Sweden's use of nuclear power. What specific questions would you ask of scientists and energy experts before making a final policy recommendation? What would you like the nation's energy mix to look like 10 years in the future? And 25 years in the future? What actions would need to be taken to reach your goals?
5. **THINK IT THROUGH** You are the head of the national department of energy in a nation that has just experienced a minor accident at one of its nuclear plants. A partial meltdown released radiation, but the radiation was fully contained inside the containment building, and there were no health impacts on area residents. However, citizens are terrified, and the media are highlighting the dangers of nuclear power. Your nation relies on its five nuclear plants for 25% of its energy and 50% of its electricity needs. It has no fossil fuel deposits and recently began a promising but still-young program to develop renewable energy options. What will you tell the public at your next press conference, and what policy steps will you recommend taking to ensure a safe and reliable national energy supply?
6. **THINK IT THROUGH** You are an investor and would like to invest in alternative energy. You are considering buying stock in companies that (1) construct nuclear reactors, (2) build turbines for hydroelectric dams, (3) build corn ethanol refineries, (4) are ready to supply farm and forestry waste for cellulosic ethanol, and (5) are developing algae farms. For each of these companies, what questions would you research before deciding how to invest your money? How do you expect you might apportion your investments, and why?

CALCULATING Ecological Footprints

Our three conventional energy alternatives vary tremendously in their EROI (energy returned on investment; p. 520). Examine the data on EROI for each of the energy sources as provided in the figure from **The Science behind the Story** on p. 568, and enter the data in the table below.

ENERGY SOURCE	EROI
Coal (total energy)	46
Oil and gas (total energy)	
Oil sands	
Nuclear power	
Hydropower	
Ethanol	
Biodiesel	
Wind power	

1. How many units of energy would you generate by investing 1 unit of energy into producing hydropower? How many units of energy would you need to invest into producing nuclear power if you wanted to generate that same amount of energy? How many units of energy would you need to invest into producing ethanol if you wanted to generate that same amount of energy?
2. Based on EROI values, is it more efficient to get petroleum from conventional oil or from oil sands? Which source would you guess has a larger ecological footprint, based on EROI values?
3. Let's say you wanted to generate 130 units of energy from biodiesel. How many units of energy would you need to invest?
4. Based on EROI values alone, which energy sources would you advocate that society use? Which would you urge society to avoid? What other issues, besides EROI, are worth considering when comparing energy sources?

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CHAPTER 21

New Renewable Energy Alternatives

