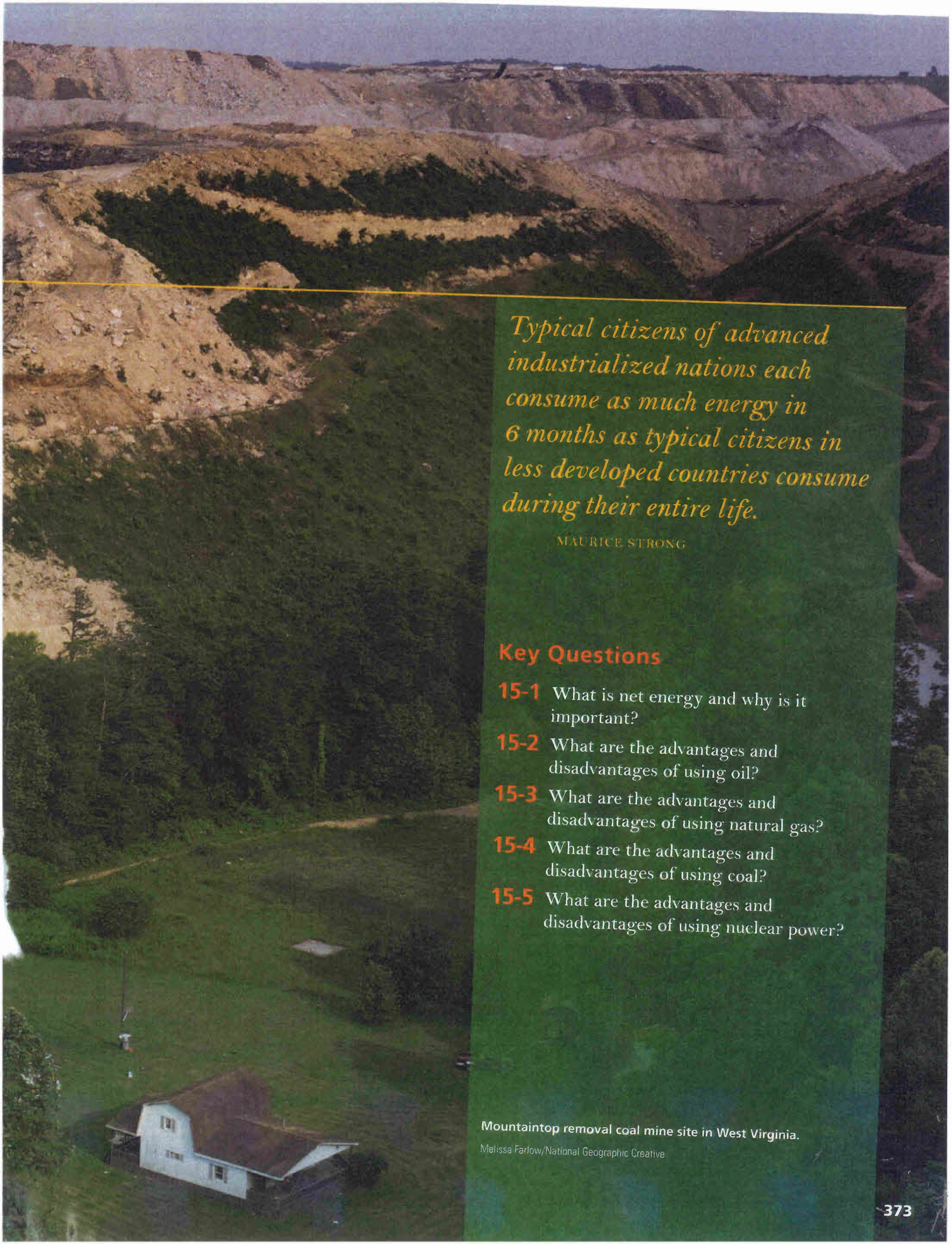


Typical citizens of advanced industrialized nations each consume as much energy in 6 months as typical citizens in less developed countries consume during their entire life.

MAURICE STRONG

Key Questions

15-1 What is net energy and why is it important?

15-2 What are the advantages and disadvantages of using oil?

15-3 What are the advantages and disadvantages of using natural gas?

15-4 What are the advantages and disadvantages of using coal?

15-5 What are the advantages and disadvantages of using nuclear power?

Mountaintop removal coal mine site in West Virginia.

Melissa Farlow/National Geographic Creative

CORE CASE STUDY Is the United States Entering a New Oil and Natural Gas Era?

Oil and natural gas are the two most widely used energy resources in the United States (Figure 15-1). There are signs that U.S. oil and natural gas production could increase sharply.

Between 1985 and 2008, oil production in the United States fell while consumption kept rising, and oil imports rose to make up the difference between consumption and production. However, since 2008, U.S. oil production has increased somewhat, largely because high oil prices and improved drilling and extraction technology have made it profitable to extract oil that is dispersed and tightly held in dense formations of shale rock.

According to some oil economists and the International Energy Agency, if oil production increases as projected and oil prices remain at $50 a barrel or higher, the United States could become the world's largest oil producer, probably sometime before 2020. Such a boom in domestic oil production would create large numbers of jobs, stimulate the U.S. economy, and reduce the country's expensive dependence on imported oil.

Since 1999, natural gas drilling and production have also increased dramatically, especially the extraction of natural gas held tightly within shale rock using the same drilling and extraction technology that is used to pull tightly held oil from shale rock. By 2011, this growing supply had led to sharply lower U.S. natural gas prices and made the United States the world's leading natural gas producer. If U.S. natural gas production from shale rock continues to grow as projected, and if natural gas prices do not rise significantly, natural gas could displace environmentally harmful coal as the country's largest source of electricity within three to four decades.

However, there are two major problems with this scenario. One is that the large-scale removal of natural gas and oil held tightly in shale rock requires huge amounts of water and also produces heavily polluted wastewater. This, along with leaks from gas and oil well piping systems, could contaminate shallow aquifers that feed many drinking water wells, as well as deep aquifers, unless the entire drilling, extraction, and wastewater treatment process is strictly monitored and regulated to protect drinking water.

A second problem is that by burning more carbon-containing oil, natural gas, and coal, we will continue to release growing quantities of carbon dioxide (CO_2) and methane (CH_4) into the atmosphere faster than they can be removed by the carbon cycle (see Figure 3-17, p. 66). Computer models project that rising atmospheric levels of these greenhouse gases will play a key role in changing the world's climate in potentially very harmful ways during this century.

In this chapter, we discuss the advantages and disadvantages of using nonrenewable fossil fuels (such as oil, natural gas, and coal) and nuclear power. In the next chapter, we look at the advantages and disadvantages of improving energy efficiency and using a variety of renewable energy resources.

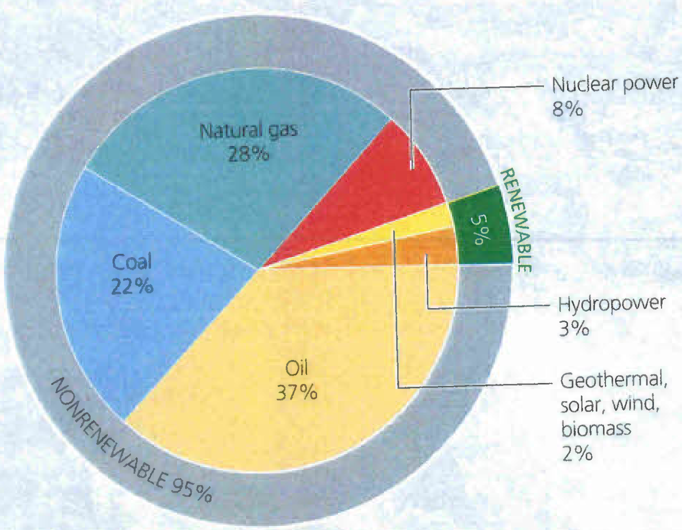


Figure 15-1 Sources of energy used in the United States in 2011. Oil, the most widely used resource, is removed from deposits underground and from deep under the ocean floor in some coastal areas (see photo).

(Compiled by the authors using data from U.S. Energy Information Administration, British Petroleum, and International Energy Agency.)

15-1 What Is Net Energy and Why Is It Important?

CONCEPT 15-1

Energy resources vary greatly in their *net energy yields*—the amount of energy available from a resource minus the amount of energy needed to make it available.

Net Energy Is the Only Energy That Really Counts

It takes energy to produce energy. For example, before oil becomes useful to us, it must be found, pumped up from beneath the ground or ocean floor (see photo in Figure 15-1), transferred to a refinery, converted to gasoline and other fuels and a variety of other widely used chemicals, and delivered to consumers. Each of these steps uses high-quality energy, mostly obtained by burning fossil fuels, especially gasoline and diesel fuel produced from oil. Because of the second law of thermodynamics (see Chapter 2, p. 43), which we cannot violate, some of the high-quality energy used in each step is automatically wasted and degraded to lower-quality energy, mostly heat that ends up in the environment.

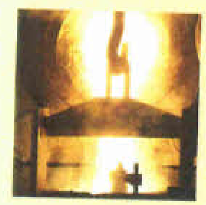
The usable amount of high-quality energy available from an energy resource is its **net energy yield.** It is the total amount of high-quality energy available from an energy resource minus the high-quality energy needed to make the energy available (Concept 15-1). It is also related to the *energy return on investment (EROI)*—the energy obtained per unit of energy used to obtain it. Suppose that it takes about 9 units of high-quality energy to produce 10 units of high-quality energy from an energy resource. Then the net energy yield is only 1 unit of energy.

Net energy is like the net profit earned by a business after it deducts its expenses. If a business has $1 million in sales and $900,000 in expenses, its net profit is $100,000.

Figure 15-2 shows generalized net energy yields for energy resources and systems that generate electricity, heat homes and buildings, produce high-temperature heat for industrial processes, and provide transportation. It is based on several sources of scientific data and classifies estimated net energy yields as high, medium, low, or negative (negative being a net energy loss).

Electricity	Net Energy Yield
Energy efficiency	High
Hydropower	High
Wind	High
Coal	High
Natural gas	Medium
Geothermal energy	Medium
Solar cells	Low to medium
Nuclear fuel cycle	Low
Hydrogen	Negative (Energy loss)

High-Temperature Industrial Heat	Net Energy Yield
Energy efficiency (cogeneration)	High
Coal	High
Natural gas	Medium
Oil	Medium
Heavy shale oil	Low
Heavy oil from tar sands	Low
Direct solar (concentrated)	Low
Hydrogen	Negative (Energy loss)



Space Heating	Net Energy Yield
Energy efficiency	High
Passive solar	Medium
Natural gas	Medium
Geothermal energy	Medium
Oil	Medium
Active solar	Low to medium
Heavy shale oil	Low
Heavy oil from tar sands	Low
Electricity	Low
Hydrogen	Negative (Energy loss)

Transportation	Net Energy Yield
Energy efficiency	High
Gasoline	High
Natural gas	Medium
Ethanol (from sugarcane)	Medium
Diesel	Medium
Gasoline from heavy shale oil	Low
Gasoline from heavy tar sand oil	Low
Ethanol (from corn)	Low
Biodiesel (from soy)	Low
Hydrogen	Negative (Energy loss)

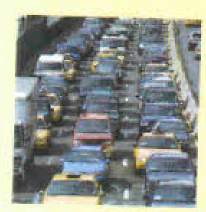


Figure 15-2 Generalized *net energy* yields for various energy systems (Concept 15-1). ***Question:*** Based only on these data, which two resources in each category should we be using?

(Compiled by the authors using data from the U.S. Department of Energy; U.S. Department of Agriculture; Colorado Energy Research Institute, *Net Energy Analysis,* 1976; Howard T. Odum and Elisabeth C. Odum, *Energy Basis for Man and Nature,* 3rd ed., New York: McGraw-Hill, 1981, and Charles A.S. Hall and Kent A. Klitgaard, *Energy and the Wealth of Nations,* New York: Springer, 2012.)

Top left: Yegor Korzh/Shutterstock.com. Bottom left: Donald Aitken/National Renewable Energy Laboratory. Top right: Serdar Tibet/Shutterstock.com. Bottom right: Michel Stevelmans/Shutterstock.com.

Some Energy Resources Need Help to Compete in the Marketplace

The following general rule can help us to evaluate the long-term economic usefulness of an energy resource based on its net energy yield: *An energy resource with a low or negative net energy yield can have a hard time competing in the marketplace with other energy alternatives that have medium to high net energy yields unless it receives financial support from the government (taxpayers) or other outside sources.* Such financial support is generally referred to as a *subsidy,* and providing it is called *subsidizing.*

For example, electricity produced by nuclear power has a low net energy yield because large amounts of high-quality energy are needed for each step in the *nuclear power fuel cycle:* to extract and process uranium ore, convert it into nuclear fuel, build and operate nuclear power plants, safely store the resulting highly radioactive wastes for thousands of years, and dismantle each plant after its useful life (typically 40–60 years) and safely store its high-level radioactive parts for thousands of years. The resulting low net energy yield for the whole nuclear fuel cycle is one reason why governments throughout the world heavily subsidize nuclear power to make it available to consumers at an affordable price. Such subsidies help to hide the true cost of the nuclear power fuel cycle and thus violate the full-cost pricing **principle of sustainability** SUSTAINABILITY (see Figure 1-5, p. 9 or back cover).

15-2 What Are the Advantages and Disadvantages of Using Oil?

CONCEPT 15-2A

Conventional crude oil is abundant and has a medium net energy yield, but using it causes air and water pollution and releases greenhouse gases to the atmosphere.

CONCEPT 15-2B

Unconventional heavy oil from oil shale rock and tar sands exists in potentially large supplies but has a low net energy yield and a higher environmental impact than conventional oil has.

We Depend Heavily on Oil

Oil is the world's most widely used energy resource (Figure 15-3). We use oil to heat our homes, grow most of our food, transport people and goods, make other energy resources available for use, and manufacture most of the things we use every day, from plastics to cosmetics to asphalt on roads.

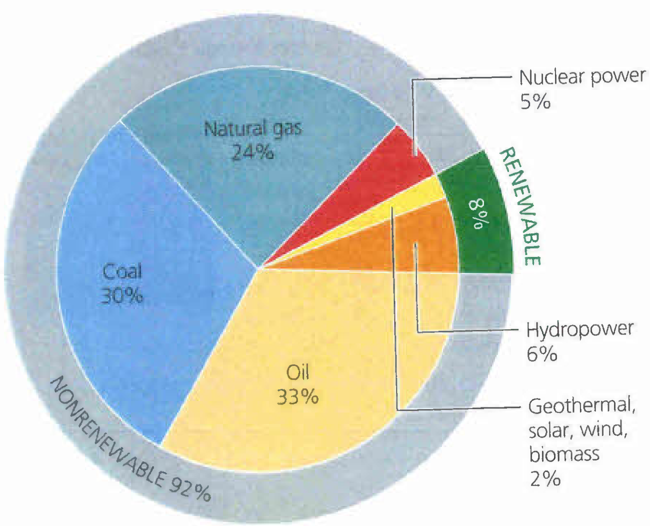


Figure 15-3 Global energy use in 2011.

(Compiled by the authors using data from British Petroleum, U.S. Energy Information Administration, and International Energy Agency.)

Crude oil, or **petroleum,** is a black, gooey liquid consisting mostly of a mix of different combustible hydrocarbons along with small amounts of sulfur, oxygen, and nitrogen impurities. It is also known as conventional or light crude oil. It was formed from the decayed remains of ancient organisms that were crushed beneath layers of rock for millions of years. The resulting liquid and gaseous hydrocarbons migrated upward through porous rock layers to collect as deposits of oil and natural gas, often trapped together beneath layers of impermeable rock.

Scientists identify potential oil deposits by using large machines to pound the earth, sending shock waves deep underground, and they measure how long it takes for the waves to be reflected back. This information is fed into computers and converted into *3-D seismic maps* of the underground that show the locations and sizes of various rock formations. Then oil companies drill holes and remove rock cores from potential oil deposit areas to learn whether there is enough oil to be extracted profitably. If there is, one or more wells are drilled and the light oil is pumped to the surface.

After years of pumping, usually a decade or so, the pressure in a well drops and its rate of crude oil production starts to decline. This point in time is referred to as **peak production** for the well. The same thing can happen to a large oil field when the overall rate of production from its numerous wells begins to drop. Global peak production would occur when the rate of global production of conventional oil begins to decline faster than new oil fields are found and put into production. There is disagreement over whether we have reached global peak production of conventional crude oil and when we might reach it if we have not.

Crude oil from a well cannot be used as it is. It is transported to a refinery by pipeline, truck, rail, or ship (oil tanker) where it is heated to separate it into various

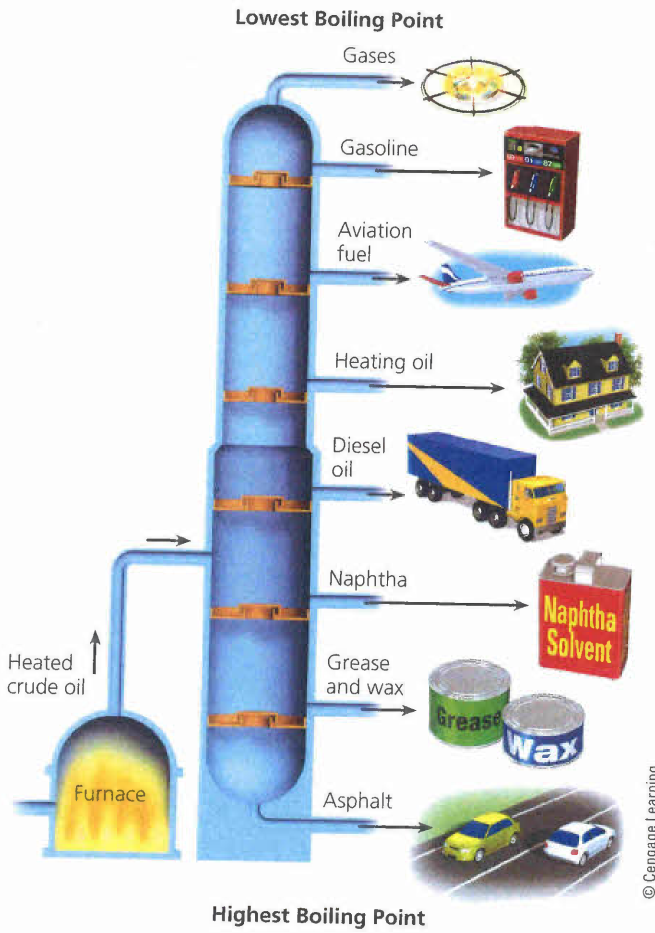


Figure 15-4 When crude oil is refined, many of its components are removed at various levels of a distillation column, depending on their boiling points. The most volatile components with the lowest boiling points are removed at the top of the column, which can be as tall as a nine-story building. The photo shows an oil refinery in Texas.

fuels and other components with different boiling points (Figure 15-4) in a complex process called **refining**. This process, like all other steps in the cycle of oil production and use, requires an input of high-quality energy and decreases the net energy yield of oil. About 2% of the products of refining, called **petrochemicals**, are used as raw materials to make industrial organic chemicals, cleaning fluids, pesticides, plastics, synthetic fibers, paints, medicines, cosmetics, ice cream, and many other products.

Are We Running Out of Conventional Oil?

We use an astonishing amount of oil. Laid end to end, the roughly 32 billion barrels of crude oil used worldwide in 2011 would stretch to about 28 million kilometers (18 million miles)—far enough to reach to the moon and back about 37 times. (One barrel of oil contains 159 liters or 42 gallons of oil.)

According to the 2012 BP Statistical Review of World Energy, in 2011, the world's three largest producers of conventional light oil, in order, were Saudi Arabia (13.2% of world production), Russia (13%), and the United States (8%, see the Case Study that follows). The International Energy Agency projects that by 2017, the United States is likely to be the world's largest oil producer. In 2011, the world's three largest oil consumers were the United States (using 21% of all oil produced), China (11%), and Japan (5%). The Earth Policy Institute projects that, by 2035, China will be using 4 times more oil than the United States.

How much oil is there? No one knows, although geologists have provided us with estimates of amounts existing in identified deposits. However, not all such deposits can be exploited at a profit, and oil that cannot be extracted profitably is not considered to be available. Availability is determined mostly by five factors that can change over time: **(1)** the demand for the oil, **(2)** the technology used to make it available, **(3)** the rate at which we can remove the oil, **(4)** the cost of making it available, and **(5)** its market price.

Available deposits are called **proven oil reserves**—deposits from which the oil can be extracted profitably at current prices with current technology. Proven oil reserves are not fixed. For example, recently improved oil extraction technology (Science Focus 15.1) and higher oil prices have made it profitable to extract light oil that is tightly held in layers of shale rock, and this has increased proven oil reserves.

The world is not about to run out of conventional light oil in the near future, but the easily extracted cheap oil that supports our economies and lifestyles may be running low. Most of the world's oil comes from huge oil fields that were discovered decades ago. Production from many of these fields has begun to decline and new fields are getting harder to find and more expensive to develop.

We can produce more conventional light oil from far offshore in deep ocean seabed deposits and from areas near the Arctic Circle. We can also rely more on unconventional heavy oil—a type of crude oil that does not flow as easily as light oil—from depleted oil wells and other sources. But use of these sources of oil results in lower net energy yields, higher production costs, and higher environmental impacts. Having to rely more on such sources leaves us with three major options: **(1)** learn to live with much higher oil prices and thus higher prices on many other items; **(2)** extend supplies by using oil much more

SCIENCE FOCUS 15.1

REMOVING TIGHTLY HELD OIL AND NATURAL GAS BY DRILLING SIDEWAYS AND FRACKING

Geologists have known for decades about vast deposits of oil and natural gas that are widely dispersed and tightly held in dense layers of shale rock formations found in many areas of the United States, including North Dakota, Texas, and Pennsylvania (see map in Figure 33, p. S58, in Supplement 6).

Until recently, it cost too much to extract such oil and natural gas from shale rock. This situation has changed because of high oil prices along with the use of two newer extraction technologies (Figure 15-A). One is **horizontal drilling**, a method of drilling first vertically to a certain point, then bending the flexible well bore and drilling horizontally. This method is used to gain greater access to oil and gas deposits located within layers of shale or other rock deposits. Usually, wells are drilled vertically for 1.6–2.4 kilometers (1–1.5 miles) or more and then horizontally for up to 1.6 kilometers (1 mile). Two or three horizontally drilled wells can often produce as much oil as 20 vertical wells, which reduces the area of land damaged by drilling operations.

The second technology, called **hydraulic fracturing** or **fracking**, is then used to free the tightly held oil and natural gas. After perforated tubes with explosive charges create fissures in the rock, high-pressure pumps shoot a mixture of water, sand, and chemicals into the well. When the pressure builds enough to fracture the rock, the mixture of water, sand, and chemicals flows into the cracks and creates more cracks and weak spots. The sand allows the cracks to remain open so that the oil or natural gas can flow out of the well to the surface.

Over a period of time this process is repeated 7–10 times per well. Much of the water that is contaminated with fracking chemicals and various other chemicals released from the rock (some of them hazardous) flows back to the surface. This contaminated water can be cleaned up and recycled. Other options are to store it in lined holding ponds or to inject it into deep underground hazardous waste disposal wells. Currently, about 80% of this contaminated water is injected into disposal wells. The rest is either recycled or stored in lined ponds. Using fracking to extract oil or natural gas costs about 5–10 times more than a conventional oil or natural gas well, and the supply is depleted about twice as fast.

The growing use of these two extraction technologies will be a key to the projected new era of oil and natural gas production in the United States (**Core Case Study**), provided the market prices of oil and natural gas remain high enough to make it profitable. However, there are some potentially serious environmental problems related to widespread use of these technologies. We discuss these in Section 15-3.

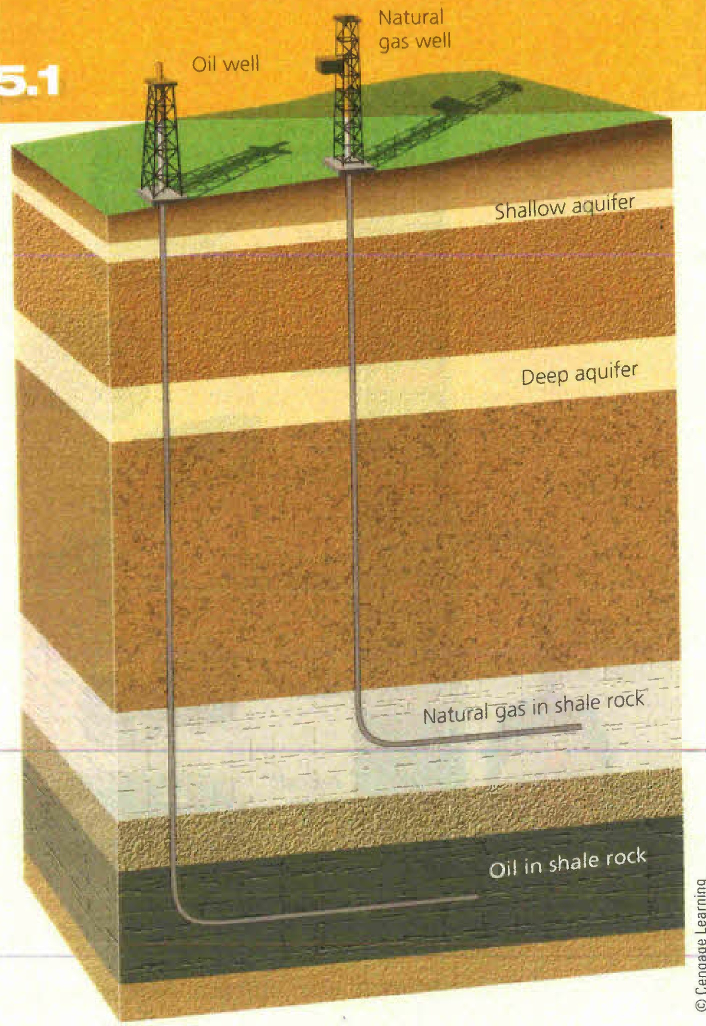


Figure 15-A Horizontal drilling and hydraulic fracturing, or fracking, are being used to release large amounts of oil and natural gas that are tightly held in shale rock formations.

Critical Thinking

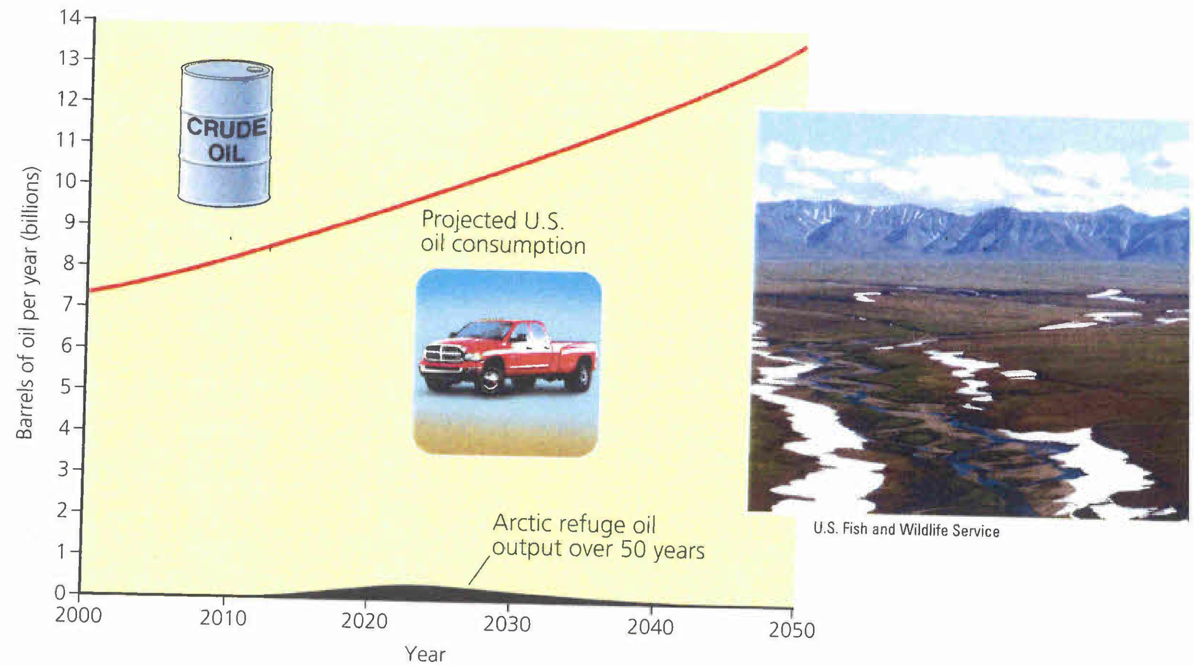
Why do you think horizontal drilling allows better access to tightly held oil and natural gas deposits than does drilling vertically into such deposits?

efficiently, for example, by sharply improving vehicle fuel efficiencies; and **(3)** use other energy resources.

The 12 countries that make up the Organization of Petroleum Exporting Countries (OPEC) have about 72% of the world's proven crude oil reserves and thus are likely to control most of the world's oil supplies for many years to come. Today, OPEC's members are Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, United Arab Emirates, and Venezuela. Other countries, including Canada and Russia, also have large oil reserves. According to BP, in 2011, Venezuela had the largest portion (18%) of the world's proven light oil reserves, followed by

Figure 15-5 The amount of conventional light crude oil that might be found in the Arctic National Wildlife Refuge, if developed and extracted over 50 years, is a tiny fraction of the projected U.S. demand for oil.

(Compiled by the authors using data from U.S. Department of Energy and U.S. Geological Survey.)



U.S. Fish and Wildlife Service

Saudi Arabia (16%), Canada (11%), Iran (9%), Iraq (9%), Kuwait (6%), the United Arab Emirates (6%), and Russia (5%). The world's three largest users of light oil—the United States, China, and Japan—have, in order, only about 2%, 1%, and 0.003% of the world's proven crude oil reserves.

Based on data from the U.S. Department of Energy and the U.S. Geological Survey, if global consumption of conventional light oil continues to grow at about 2% per year, then:

- Saudi Arabia, with the world's second largest crude oil reserves, could supply the world's demand for oil for about 7 years.
- Estimated unproven crude oil reserves under Alaska's Arctic National Wildlife Refuge (ANWR) (see Figure 31, p. S56, in Supplement 6) would meet the world's demand for 1–5 months and U.S. demand for 7–24 months (Figure 15-5).
- The Arctic Circle holds enough technically recoverable crude oil to meet the global demand for about 3 years at high production costs.

Bottom line: to keep using conventional light oil at the projected rate of increase, we must expand global proven crude oil reserves by an amount equal to Saudi Arabia's current reserves every 7 years. Most oil geologists say this is highly unlikely.

Use of Conventional Oil Has Environmental Costs

The extraction, processing, and burning of conventional crude oil has severe environmental impacts, including land disruption, greenhouse gas emissions, and other forms of air pollution, water pollution, and loss of biodiversity.

A critical and growing problem is that burning oil or any carbon-containing fossil fuel releases the greenhouse gas CO_2 into the atmosphere. According to most of the world's top climate scientists, this has been warming the atmosphere and will contribute to projected climate change during this century. Currently, burning oil, mostly as gasoline and diesel fuel for transportation, accounts for 43% of global CO_2 emissions, which have been increasing rapidly (see Figure 14, p. S70, in Supplement 7).

Another problem is that, as easily accessible deposits are becoming depleted, oil producers are turning to oil that is buried deep underground in sensitive areas and under the ocean floor in certain coastal areas. As was revealed in the catastrophic oil spill in the Gulf of Mexico in 2010, going to these harder-to-reach deposits greatly increases the risk of severe environmental degradation.

Figure 15-6 lists the advantages and disadvantages of using conventional oil as an energy resource.

CASE STUDY

Oil Production and Consumption in the United States

The United States gets about 87% of its commercial energy from fossil fuels, with 37% coming from oil (Figure 15-1). Currently, oil production in the United States, especially from shale rock, is increasing rapidly and could make the country the world's largest oil producer by 2020. However, oil production from shale rock is likely to decline over the next two decades as the richest deposits are depleted. The long-term problem for the United States is that it uses about 21% of the oil produced globally but produces only 9% of the world's oil

Trade-Offs

Conventional Oil

Advantages	Disadvantages
Ample supply for several decades	Water pollution from oil spills and leaks
Net energy yield is medium but decreasing	Environmental costs not included in market price
Low land disruption	Releases CO_2 and other air pollutants when burned
Efficient distribution system	Vulnerable to international supply interruptions

Figure 15-6 Using conventional light oil as an energy resource has advantages and disadvantages. ***Questions:*** Which single advantage and which single disadvantage do you think are the most important? Why? Do the advantages of relying on conventional light oil outweigh its disadvantages? Explain.

Photo: Richard Goldberg/Shutterstock.com

and has only about 2% of the world's proven conventional oil reserves. Also, much of its supply lies under environmentally sensitive land and coastal areas that are expensive to develop.

Since 1982, oil consumption in the United States has greatly exceeded domestic production. This helps to explain why, in 2012, the United States imported 39% of its crude oil (compared to 24% in 1970 and 60% in 2005). The decrease in dependence on oil imports between 2005 and 2012 resulted from a combination of a weak economy and reduced oil consumption due to improvements in fuel efficiency. Also, there was a slight increase in U.S. oil production between 2008 and 2012, mostly because of increased production of oil from shale rock deposits.

In 2012, the five largest suppliers of oil imported into the United States were, in order, Canada, Saudi Arabia, Venezuela, Mexico, and Iraq. By importing oil, the United States transfers a massive amount of its wealth to these oil-producing countries.

Can the United States significantly reduce its dependence on oil imports by producing its own oil faster than its current oil supply is being depleted? Some say "yes" and project that domestic oil production will increase dramatically over the next few decades—especially from oil found in shale rock. They argue that this will lead to a new era of oil production in the United States (**Core Case Study**). The U.S. Energy Information Agency (EIA) estimates that increased production of oil from shale rock could continue to reduce U.S. dependence on imported oil.

However, we do not know how much of the oil held tightly in shale rock deposits can be extracted profitably and at an acceptable environmental cost. For example, horizontal drilling and fracking produce massive amounts of contaminated wastewater. And there is no guarantee that the well pipes and casing in any fracking operation will not leak the toxic chemicals used in and produced by fracking into underground drinking water supplies.

In addition, experience indicates that production of oil from shale rock beds drops off about twice as fast as it does in most conventional oil fields. Thus, long-term, profitable oil production from these resources may be overestimated. And producing oil from shale rock using current technology will be profitable only as long as the price of oil is at least $50 a barrel. In addition, this oil would be developed with high production costs, lower net energy yields, and potentially high environmental impacts.

Heavy Oil from Oil Shale Rock

A potential supply of heavy oil is *shale oil*. It is produced by mining, crushing, and heating oil shale rock (Figure 15-7, left) to extract a mixture of hydrocarbons called *kerogen* that can be distilled to produce shale oil (Figure 15-7, right). Before the thick shale oil is sent by pipeline to a refinery, it must be heated to increase its flow rate and processed to remove sulfur, nitrogen, and other impurities, which decreases its net energy yield. (These kerogen-containing deposits found in oil shale rock differ from the oil dispersed and tightly held in shale rock, discussed in the **Core Case Study**.)

About 72% of the world's estimated oil shale rock reserves are buried deep in rock formations located primarily under government-owned land in the U.S. states of Colorado, Wyoming, and Utah in an area known as the Green River formation (see map in Figure 31, p. S56, in Supplement 6). The U.S. Bureau of Land Management estimates that these deposits contain an amount of potentially recoverable heavy oil equal to almost 4 times the amount in Saudi Arabia's proven reserves of conventional oil. Estimated potential global supplies of unconventional heavy shale oil are about 240 times larger than estimated global supplies of conventional crude oil.

The problem is that it takes considerable energy, money, and water to extract kerogen from shale rock and convert it to shale oil. Thus, its net energy yield is low. Also, the process pollutes large amounts of water and releases 27–52% more CO_2 into the atmosphere per unit of energy produced than does producing conventional crude oil (**Concept 15-2B**). In 2011, the U.S. Bureau of Land Management stated that unless oil prices rise sharply: "There are no economically viable ways yet known to extract and process oil shale for commercial purposes."

Heavy Oil from Tar Sands

A growing source of heavy oil is **tar sands**, or **oil sands**, which are a mixture of clay, sand, water, and a combustible organic material called *bitumen*—a thick, sticky, tarlike heavy oil (Figure 15-8) with a high sulfur content.

Figure 15-7 Heavy shale oil (right) can be extracted from oil shale rock (left).

Figure 15-8 This gooey tar, or bitumen, with the consistency of peanut butter, was extracted from tar sands in Alberta, Canada, to be converted to heavy synthetic oil.

Northeastern Alberta in Canada has three-fourths of the world's tar sands resource in sandy soil under a vast area of remote boreal forest (see Figure 7-13, bottom photo, p. 156). If we include its conventional light oil and heavy oil from tar sands, Canada has the world's third largest proven oil reserves.

The big drawback to using tar sands is that developing this resource has major harmful impacts on the land (Figure 15-9), air, water, wildlife, and climate, compared to developing conventional light oil and tightly held oil from shale rock (**Concept 15-2B**). Before the mining takes place, the overlying boreal forest is clear-cut, wetlands are drained, and rivers and streams are sometimes diverted. Next the overburden of sandy soil, rocks, peat, and clay is stripped away to expose the tar sands deposits. Then five-story-high electric power shovels dig up the sand and load it into three-story-high trucks, which carry it to an upgrading plant. There, the tar sands are mixed with hot water and steam to extract the bitumen. Next, the bitumen is heated by natural gas in huge cookers and converted into a low-sulfur, synthetic, heavy crude oil that has to be processed further to allow it to flow through pipelines to a refinery.

According to a 2009 study by CERA, an energy consulting group, the process of extracting, processing, and refining bitumen from tar sands into heavy oil releases 3 to 5 times more greenhouse gases per barrel of oil produced than does extracting and producing conventional light oil. Part of this process is the removal of the boreal forest and peat deposits lying above the tar sands deposits. Left undisturbed, these forests and peatlands help to reduce the threat of projected climate change by storing great amounts of carbon. Much of this carbon is released to the atmosphere as CO_2 when the forests and peatlands are removed, which adds to the threat of global climate disruption.

Although tar sand sites can be planted with vegetation after the strip mining, such restoration is expensive and rare and cannot match the capacity of ancient peatlands and boreal forests for absorbing carbon and helping to offset projected climate dis-

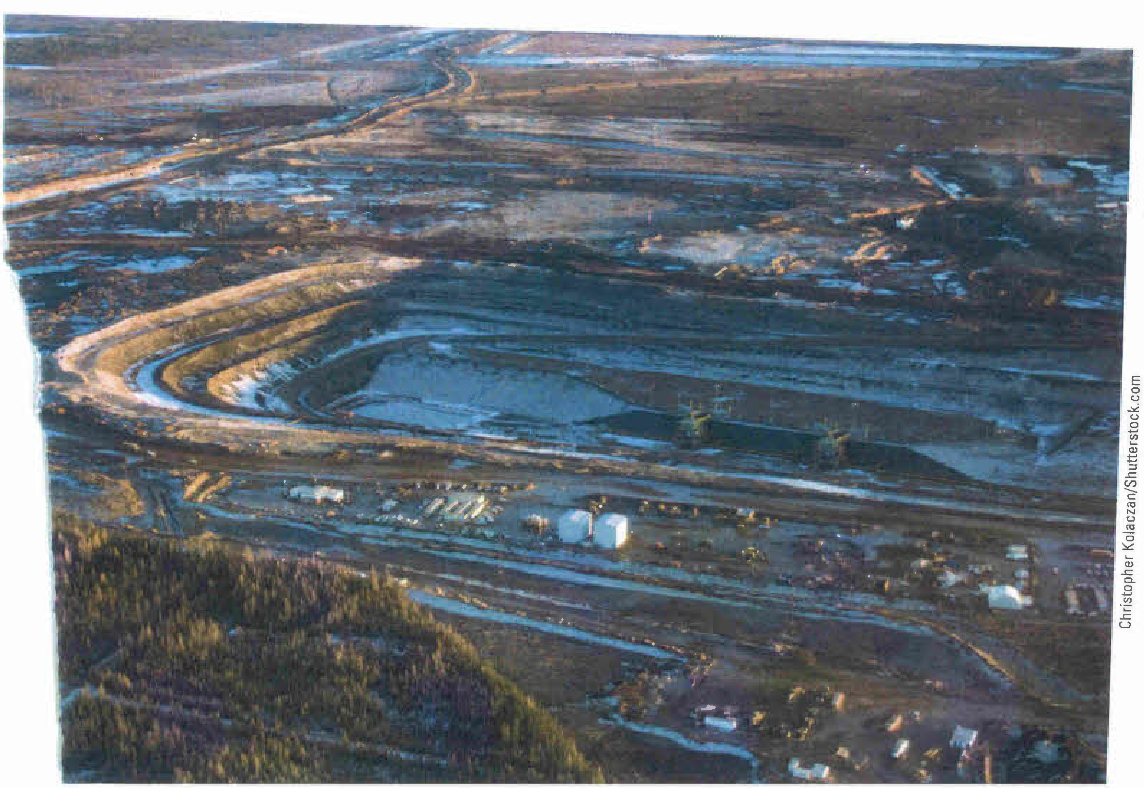


Figure 15-9 Tar sands mining operation in Alberta, Canada.

ruption. Also, some studies have estimated that the conversion of tar sands to heavy oil produces only 5–20% more greenhouse gases than does conventional oil production. However, these studies did not take into account the entire production process, including the loss of carbon-absorbing peatlands and boreal forest.

In addition, this process uses huge amounts of water and creates lake-size tailings ponds containing toxic sludge and wastewater. Many migrating birds die trying to get water and food from these ponds. Also, the dikes of compacted sand surrounding the tailings ponds have the potential to leak and release large volumes of toxic sludge onto nearby land and into streams and rivers.

Finally, it takes a great deal of energy to produce oil from tar sands, which involves burning natural gas to provide heat for the bitumen cookers and using diesel fuel to run the massive vehicles and machinery. This too adds to the pollution of air, water, and land and to the emissions of greenhouse gases.

Figure 15-10 lists the major advantages and disadvantages of using heavy oil from tar sands and from oil shale rock as an energy resource.

Trade-Offs

Heavy Oils from Oil Shale and Tar Sand

Advantages	Disadvantages
Large potential supplies	Low net energy yield
Easily transported within and between countries	Releases CO_2 and other air pollutants when produced and burned
Efficient distribution system in place	Severe land disruption and high water use

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Figure 15-10 Using heavy oil from tar sands and from oil shale rock as an energy resource has advantages and disadvantages (Concept 15-2). ***Questions:*** Which single advantage and which single disadvantage do you think are the most important? Why? Do the advantages of relying on heavy oil from these sources outweigh the disadvantages? Explain.

Photo: Christopher Kolaczan/Shutterstock.com

15-3 What Are the Advantages and Disadvantages of Using Natural Gas?

CONCEPT 15-3

Conventional natural gas is more plentiful than oil, has a medium net energy yield and a fairly low production cost, and is a clean-burning fuel, but producing it has created environmental problems.

Natural Gas Is a Useful, Clean-Burning, but Not Problem-Free Fossil Fuel

Natural gas is a mixture of gases of which 50–90% is methane (CH_4). It also contains smaller amounts of heavier gaseous hydrocarbons such as propane (C_3H_8) and butane (C_4H_{10}), and small amounts of highly toxic hydrogen sulfide (H_2S). This versatile fuel has a medium net energy yield (Figure 15-2) and is widely used for cooking, heating space and water, and industrial purposes, including production of most of the world's nitrogen fertilizer. It can also be used as a fuel for cars and trucks and for natural gas turbines used to produce electricity in power plants.

This versatility helps to explain why natural gas provides about 28% of the energy consumed in the United States. It burns cleaner than oil and much cleaner than coal, and when burned completely, it emits about 30% less CO_2 than oil and about 50% less than coal.

Conventional natural gas is often found in deposits lying above deposits of conventional oil. It also exists in tightly held deposits in shale rock and can be extracted through horizontal drilling and fracking (see Science Focus 15.1). See Figure 33, p. S58, in Supplement 6 for a map of major U.S. natural gas shale rock deposits. In the United States and many other countries, natural gas is distributed to users by a large network of underground pipelines.

When a natural gas deposit is tapped, propane and butane gases can be liquefied under high pressure and removed as **liquefied petroleum gas (LPG)**. LPG is stored in pressurized tanks for use mostly in rural areas not served by natural gas pipelines. Natural gas can also be transported across oceans, by converting it to **liquefied natural gas (LNG)** at a high pressure and at a very low temperature. This highly flammable liquid is transported in refrigerated tanker ships. At its destination port, it is heated and converted back to the gaseous state and then distributed by pipeline. LNG has a low net energy yield, because more than a third of its energy content is used to liquefy it, process it, deliver it to users by ship, and convert it back to natural gas.

In 2011, the International Energy Agency estimated that recoverable conventional supplies of natural gas could meet the current global demand for about 120 years, and that potentially recoverable unconventional supplies of natural gas could sustain current global production for 250 years. GOOD NEWS That year, according to BP's 2012 Annual Review of World Energy, Russia had about 21% of the world's proven conventional natural gas reserves, followed by Iran (16%), Qatar (12%), and Turkmenistan (12%). China and India, with their rapidly growing economies, have only 1.5% and 0.6%, respectively, of the world's proven natural gas reserves and the United States has only 4%. Japan has no significant natural gas reserves and depends on imports of expensive LNG.

In 2011, the world's three largest producers of natural gas were the United States (with 20% of global total production), Russia (19%), and Canada (5%). In that year, the United States used about 22% of the world's production. (See Figure 5, p. S66, in Supplement 7 for a graph of U.S. natural gas consumption between 1980 and 2012, with projections to 2040.) U.S. natural gas production has been increasing rapidly, mostly because of development of the technology used to extract tightly held natural gas from shale rock (Figure 15-A). This source accounted for about 60% of U.S. natural gas production in 2011 (up from 2% in 2000). Thus, the United States does not have to rely on natural gas imports.

The demand for natural gas in the United States is projected to more than double between 2010 and 2050. If much of this demand is met by increased production of natural gas from shale rock, the United States could continue meeting its needs for natural gas from domestic resources. If natural gas prices remain affordable, such a trend would reduce the use of coal-burning power plants and make new nuclear power plants even more uneconomical than they are now. This could also slow the shift to greater use of renewable solar and wind energy resources.

However, U.S. natural gas producers would like to export natural gas as LPG to countries where natural gas prices are much higher than in the United States. Chemical industries and utilities that use natural gas to provide heat and produce electricity oppose this because it could decrease the supply and raise domestic natural gas prices.

There are some potential problems that could temper this rosy outlook for natural gas. In 2011, the U.S. Geological Survey cut its nationwide estimate of recoverable shale gas by 50% and pointed out that natural gas production from shale rock tends to peak and drop off much faster than does production from conventional natural gas wells. One question is whether the rate of increased production of natural gas from shale rock can exceed the rate of decline in conventional natural gas production from aging fields. Another major potential drawback is the environmental problems related to greatly increasing U.S. production of natural gas from shale rock, as discussed in the Case Study that follows.

Figure 15-11 lists the advantages and disadvantages of using conventional natural gas as an energy resource.

Trade-Offs

Conventional Natural Gas

Advantages	Disadvantages
Ample supplies	Low net energy yield for LNG
Versatile fuel	Production and delivery may emit more CO_2 and CH_4 per unit of energy produced than coal
Medium net energy yield	Fracking uses and pollutes large volumes of water
Emits less CO_2 and other air pollutants than other fossil fuels when burned	Potential groundwater pollution from fracking

Figure 15-11 Using conventional natural gas as an energy resource has advantages and disadvantages. ***Questions:*** Which single advantage and which single disadvantage do you think are the most important? Why? Do you think that the advantages of using conventional natural gas outweigh the disadvantages? Explain.

Photo: Werner Muenzker/Shutterstock.com

CASE STUDY

Natural Gas Production and Fracking in the United States: Environmental Problems and Solutions

The production of natural gas from shale rock deposits involves drilling wells; using huge amounts of water, sand, and chemicals to frack the gas; bringing up the natural gas along with the resulting toxic wastewater; dealing with this wastewater; and transporting the natural gas to users through underground pipelines. At several points in this production process, natural gas can leak into the atmosphere and into underground sources of drinking water for nearby homes and communities. Despite the industry's attempts to solve this problem, natural gas has leaked from loose pipe fittings and faulty cement seals in natural gas well bore holes, as well as from pipelines and cutoff valves used to deliver natural gas.

Drinking water contaminated by natural gas can catch fire (Figure 15-12), and some home owners have had to install expensive systems to remove the natural gas to prevent explosions. According to a 2012 study by the National Academy of Sciences, people living within 900 meters (3,000 feet) of a natural gas well are likely to have up to 17 times more methane in their groundwater than those who live farther away.

Within a decade or two, there may be at least 100,000 more natural gas wells using fracking technology, according to the U.S. Energy Information Administration. Without increased monitoring and regulation of the entire natural gas production process, including fracking, the greatly increased production of natural gas (and oil) from shale rock could have several harmful environmental effects:

- Fracking requires enormous volumes of water. In water-short areas this could help to deplete aquifers, degrade aquatic habitats, and diminish the availability of water for other purposes.

MARK THIESSEN/National Geographic Creative

Figure 15-12 Natural gas fizzing from this faucet in a Pennsylvania home can be lit like a natural gas stove burner. This began happening after an energy company drilled a fracking well in the area, but the company denies responsibility. The home owners have to keep their windows open year-round to keep the lethal and explosive gas from building up in the house.

- Fracking fluids can contain several potentially hazardous chemicals that are used to reduce friction, inhibit corrosion, and stop bacterial growth. Each fracked well produces millions of gallons of wastewater that are brought to the surface along with the released natural gas. This slurry contains a mix of naturally occurring salts, toxic heavy metals, and radioactive materials leached from the rock. It also contains chemicals used in the fracking process, which natural gas companies do not have to reveal to the public. After fracking, the slurry is stored in various ways, some more secure than others, and there are several points in this complex process at which some or all of this toxic slurry could be released to contaminate nearby groundwater, surface waters, or land.
- Because fracking requires a special type of sand, some areas of the country, especially western Wisconsin, are seeing a boom in the mining of this sand. This new form of strip mining has expanded rapidly with little regulation and is destroying large areas of wildlife habitat while creating air and noise pollution in the mining areas.
- According to a 2012 study by the National Academy of Sciences and another study by the U.S. Geological Survey, in recent years, one of the major causes of hundreds of small earthquakes in 13 states has been the shifting of bedrock resulting from the high-pressure injection of large amounts of wastewater from fracking and other industrial activities into deep underground storage wells. The pressure involved is typically 9 times higher than the pressure required to crush a submarine on its deepest dive. Such earthquakes could release hazardous wastewater into aquifers and cause breaks in the steel lining and cement seals of oil and gas well pipes. In 2012, the U.S. state of Ohio shut down a deep well used for the disposal of fracking wastewater after several small earthquakes occurred in the vicinity of the well.
- In 2011, ecologist Robert Howarth and geoscientist David Hughes, in separate studies, both estimated that emissions of climate-changing CH_4 and CO_2 from the entire process for supplying and burning natural gas from shale rock are higher than those from supplying and burning conventional natural gas and coal. If these preliminary estimates are verified, the positive environmental image of natural gas—based mainly on the fact that it is relatively clean-burning and not on its entire cycle of production and use—will be tarnished.

Producers maintain that fracking is necessary for exploiting natural gas from shale deposits at an affordable cost. They point out that increased natural gas production from fracking has lowered U.S. natural gas prices and benefitted the 55% of U.S. consumers who burn natural gas. In addition, the natural gas fracking boom has created thousands of jobs and boosted local economies in some areas. And the resulting shift from coal to natural gas for producing electricity has reduced U.S. air pollution.

Producers also argue that no groundwater contamination directly due to fracking has ever been recorded, mostly because the fracking takes place far below drinking water aquifers. However, critics report that the EPA has found at least one example of drinking water contamination that resulted from fracking. They also contend that natural gas producers have squelched numerous reports of drinking water contamination from fracking by offering financial settlements to people who make such claims with the stipulation that they cannot reveal any information about the alleged contamination. Much of the contamination may have come from leaks and faulty cement seals in well pipes, which indicates inadequate inspection and regulation of the entire natural gas production process by states and the federal government.

Currently, people who rely on aquifers and streams for their drinking water in areas affected by the boom in shale gas production have little protection against pollution of their water supplies resulting from natural gas production. This is because, under political pressure from natural gas suppliers, the 2005 Energy Policy Act excluded the fracking process from certain regulations under the federal Safe Drinking Water Act. Other loopholes have also exempted natural gas production from parts of several other federal environmental laws, including the Clean Water Act, the Clean Air Act, and the National Environmental Policy Act.

In addition, people who live near fracking operations must put up with around-the-clock noise and air pollution from drilling equipment, diesel engines, trucks hauling sand, and explosions set off each time a well is fracked. Without stricter regulation and monitoring, the drilling of another 100,000 natural gas wells during the next 10–20 years will increase the risk of harmful environmental effects from the production of natural gas, which could cause a public backlash against this technology.

According to a 2010 MIT study, the harmful environmental impacts of producing natural gas from shale rock are "manageable but challenging." Some energy analysts, along with the U.S. Energy Information Agency, have suggested several ways to reduce the environmental threats arising from shale gas production (Figure 15-13). Making such changes would help us in implementing the full-cost pricing **principle of sustainability** (see Figure 1-5, p. 9 or back cover).

Solutions

- Step up research on the environmental impact of natural gas production
- Greatly increase monitoring and legal regulation of natural gas production, including regular inspections of the metal casings and concrete seals in well pipes
- Develop federal regulations on disposal, storage, treatment, and reuse of fracking wastewater
- Require complete disclosure of all chemicals used in fracking
- Require use of the least harmful chemicals available in fracking fluids
- Require testing of aquifers and drinking water wells for any chemical contamination from fracking operations before drilling begins and as long as gas extraction continues
- Overturn all exemptions for oil and natural gas production from any and all federal pollution regulations

Figure 15-13 Solutions: Reforms such as these, recommended by several energy analysts, could reduce the harmful impact of shale gas production. ***Questions:*** Which three of these steps do you think are the most important ones to take? Explain.

Unconventional Natural Gas

There are two major sources of unconventional natural gas that are both difficult and costly to exploit without high environmental impacts. One source is *coal bed methane gas* found in coal beds near the earth's surface across parts of the United States and Canada (see the map in Figure 32, p. S57, in Supplement 6). The environmental impacts of using this resource would include scarring of land, depletion of some water sources, and possible pollution of aquifers. So far it has not been economical to exploit this resource.

The other source of unconventional natural gas is *methane hydrate*—methane trapped in icy, cage-like structures of water molecules buried under arctic permafrost in tundra areas of North America, northern Europe, and Siberia. Methane hydrate is also found lying on the ocean floor in several areas of the world. So far, it costs too much to get natural gas from methane hydrates. Also, scientists warn that the projected large-scale release of methane (a potent greenhouse gas) to the atmosphere during removal and processing of this resource would likely speed up atmospheric warming and the resulting projected climate disruption.

15-4 What Are the Advantages and Disadvantages of Using Coal?

CONCEPT 15-4A

Conventional coal is plentiful and has a high net energy yield at low costs, but using it results in a very high environmental impact.

CONCEPT 15-4B

We can produce gaseous and liquid fuels from coal, but they have lower net energy yields and using them would result in higher environmental impacts than those of conventional coal.

Coal Is a Plentiful but Dirty Fuel

Coal is a solid fossil fuel formed from the remains of land plants that were buried 300–400 million years ago and exposed to intense heat and pressure over millions of years (Figure 15-14).

Coal is burned in power plants (Figure 15-15) to generate about 45% of the world's electricity, according to the International Energy Agency. This includes 93% of the electricity used in South Africa and 73% of that used in China. In the United States, mostly because of cheaper natural gas, the percentage of all electricity used that is produced by burning coal dropped from 53% in 1997 to 37% in 2012 and could drop to 30% by 2020.

Coal is also burned in industrial plants to make steel, cement, and other products. In order, the world's five largest users of coal are China, the United States, India, Russia, and Japan. In 2010, China burned 3 times more coal than the United States burned.

Coal is an abundant fossil fuel. Five countries have three-fourths of the world's proven coal reserves. They are the United States with 28% of global coal reserves (see

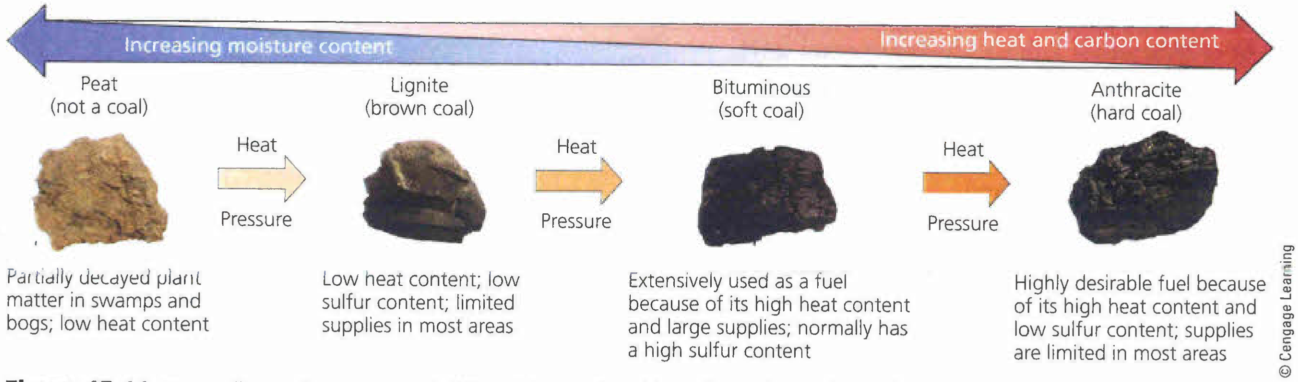


Figure 15-14 Over millions of years, several different types of coal have formed. Peat is a soil material made of moist, partially decomposed organic matter, similar to coal; it is not classified as a coal, although it is used as a fuel. These different major types of coal vary in the amounts of heat, carbon dioxide, and sulfur dioxide released per unit of mass when they are burned.

Figure 31, p. S56, in Supplement 6 for a map of major U.S. coal deposits), followed by Russia (with 18%), China (13%), Australia (9%), and India (7%). The U.S. Geological Survey estimates that identified U.S. coal reserves could last about 250 years at the current consumption rate and that identified and potential global supplies of coal could last for 200–1,100 years, depending on how rapidly they are used.

The problem is that coal is by far the dirtiest of all fossil fuels. Even when costly air-pollution-control technologies are used, burning coal pollutes the air and creates a toxic ash that is difficult to deal with. And the processes of making coal available severely degrade land and pollute water and air (see chapter-opening photo and Figures 14-12 through 14-14, p. 359).

Coal is mostly carbon but contains small amounts of sulfur, which is converted to the air pollutant sulfur dioxide (SO_2) when the coal burns. Burning coal also releases large amounts of black carbon particulates, or *soot* (Figure 15-16), and much smaller, fine particles of air pollutants such as mercury. The fine particles can get past our bodies' natural defenses that help to keep our lungs clean. According to a 2010 study by the Clean Air Task Force, fine-particle pollution in the United States, mostly from the older U.S. coal-burning power plants without the latest air-pollution-control technology, prematurely kills at least 13,000 people a year—an average of nearly 36 people every day. According to a World Bank report, burning coal in China, where air pollution control is far from adequate, causes at least 650,000 deaths a year.

Coal-burning power and industrial plants are among the largest emitters of the greenhouse gas CO_2 (Figure 15-17). China leads the world in such emissions, followed by the United States. Another problem with burning coal is that it emits trace amounts of radioactive materials as well as toxic and indestructible mercury into the atmosphere.

Finally, burning coal and removing some of the pollutants it releases from smokestack emissions produce a highly toxic ash. In the United States, about 57% of the ash is buried in landfills or in active or abandoned mines or is made into a wet slurry that is stored in holding ponds (Figure 15-18). The ash stored underground can slowly leach into groundwater, and the wet slurry can break through a pond's earthen walls, as it did at a coal ash storage pond near Knoxville, Tennessee in 2008. Such a spill can severely pollute nearby surface waters, groundwater, and land.

Coal ash is a major problem in China. According to a 2010 Greenpeace study, coal ash dumped into open landfills (Figure 15-19) is China's largest category of solid industrial waste. From these landfills, toxic chemicals are easily dispersed into the environment by wind and rain.

The Clean Coal Campaign

For decades, economically and politically powerful U.S. coal mining companies, coal-hauling railroad companies, and coal-burning power companies and industries have fought to preserve their profits by opposing measures such as stricter air pollution standards for coal-burning plants and classification of coal ash as a hazardous waste. For more than 30 years, these companies have also led the fight against efforts to classify climate-changing CO_2 as a pollutant that could be regulated by the EPA. Such regulation would likely raise their cost of doing business and make coal less competitive with cheaper sources of electricity such as natural gas and wind.

Since 2008, U.S. coal and electric utility industries have mounted a highly effective, well-financed publicity campaign built around the notion of clean coal. We can burn coal more cleanly by adding costly air-pollution-control devices to power plants. But critics argue that there could never be such a thing as clean coal. Even with stricter air pollution controls, burning coal will always involve some emissions of health-damaging air pollutants and climate-changing CO_2. It will always create indestructible and hazardous coal ash, which will actually increase with better air pollution controls, because such controls

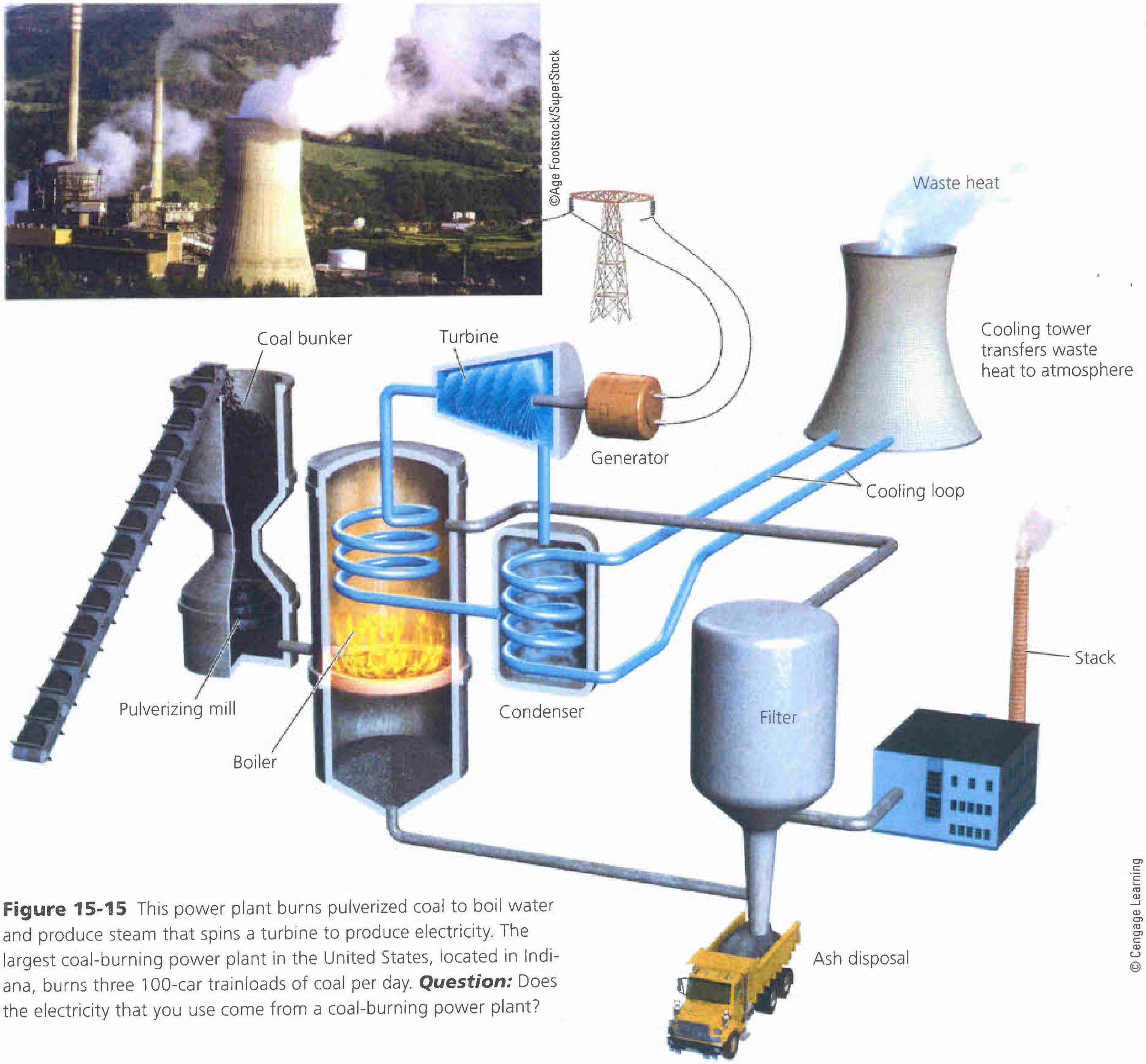


Figure 15-15 This power plant burns pulverized coal to boil water and produce steam that spins a turbine to produce electricity. The largest coal-burning power plant in the United States, located in Indiana, burns three 100-car trainloads of coal per day. ***Question:*** Does the electricity that you use come from a coal-burning power plant?

involve the creation of more coal ash. Also, mining coal will always involve disrupting land—in many cases, vast areas of land—and polluting water and air.

Coal companies and utilities can get away with talking about clean coal, and can continue to produce electricity cheaply by burning coal, primarily because the harmful environmental and health costs of producing and using coal are not included in the market prices of coal and coal-fired electricity. This violates the full-cost pricing **principle of sustainability** (see Figure 1-5, p. 9 or back cover). According to a 2010 study by Harvard Medical School's Center for Health and the Global Environment and a similar 2009 study by the U.S. National Academy of Sciences, including all such costs would double or triple the price of electricity from coal-fired power plants.

Figure 15-20 lists the advantages and disadvantages of using coal as an energy resource (**Concept 15-4A**). An important and difficult question for humanity is whether

Figure 15-16 These smokestacks on a coal-burning industrial plant emit large amounts of air pollution because the plant has inadequate air pollution controls.

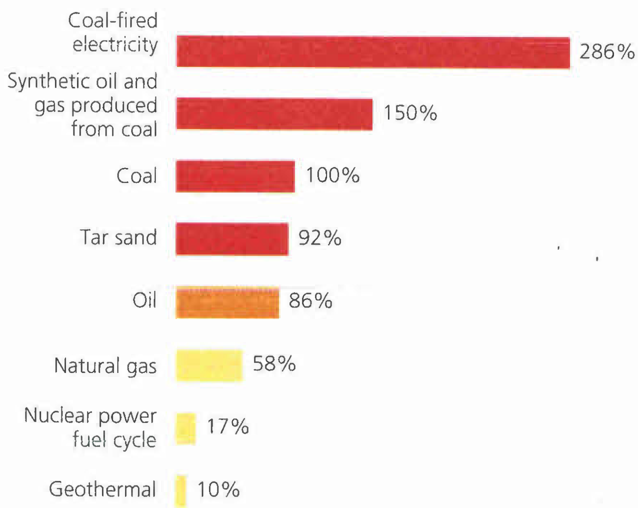


Figure 15-17 CO_2 emissions, expressed as percentages of emissions released by burning coal directly, vary with different energy resources. ***Question:*** Which of these produces more CO_2 emissions per kilogram: burning coal to heat a house, or heating with electricity generated by coal?

(Compiled by the authors using data from U.S. Department of Energy.)

we should begin shifting from use of abundant coal to using less environmentally harmful energy resources. Part of this shift would be to enact and enforce much stricter regulations on air pollution from coal-burning plants and on the handling of coal ash. In countries such as the United States, Russia, China, and India that have large reserves of coal, this would be a difficult economic and political challenge.

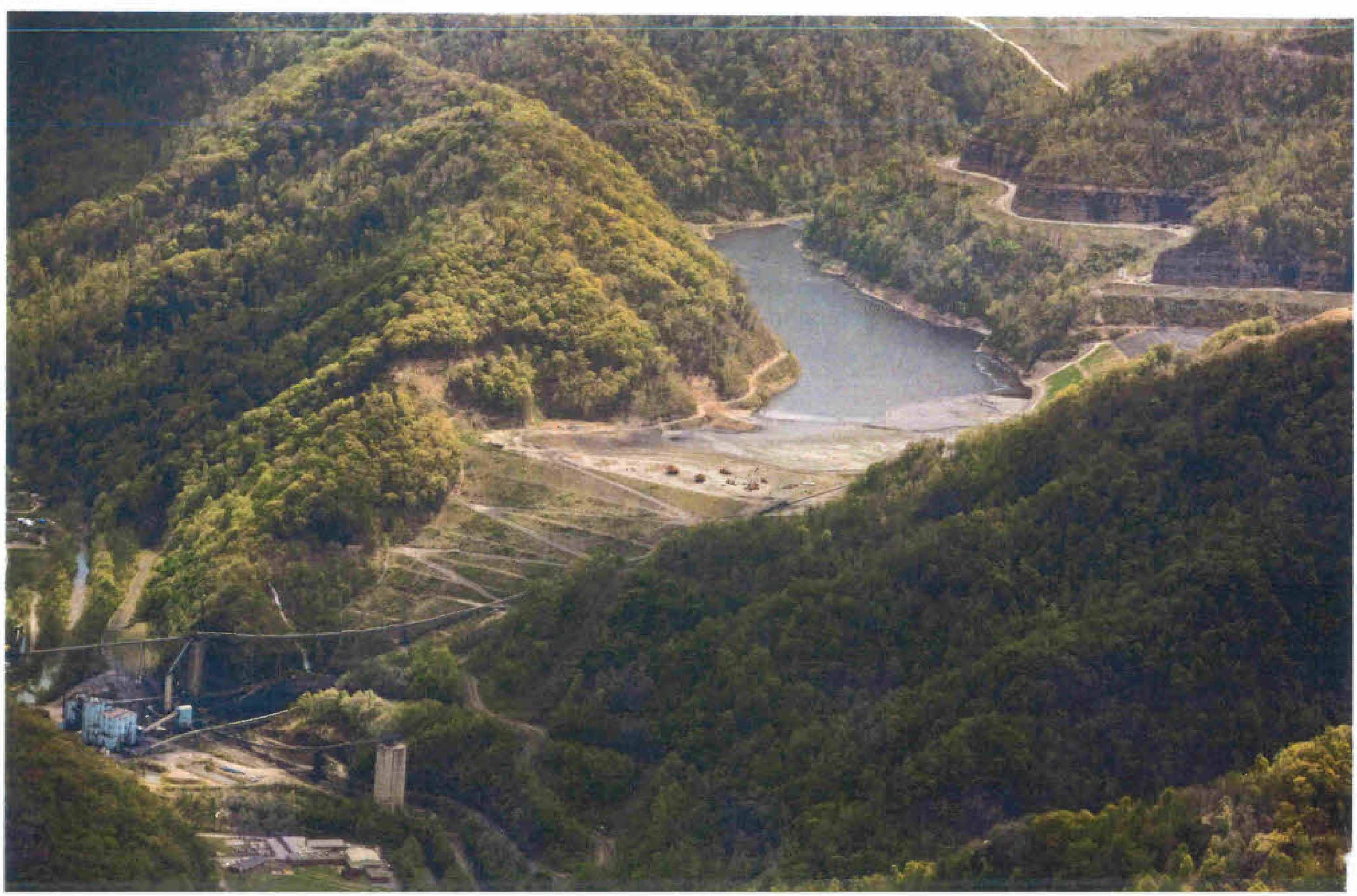
We Can Convert Coal into Gaseous and Liquid Fuels

We can convert solid coal into **synthetic natural gas (SNG)** by a process called *coal gasification,* which removes sulfur and most other impurities from coal. We can also convert it into liquid fuels such as methanol and synthetic gasoline through a process called *coal liquefaction.* These fuels, called *synfuels,* are often referred to as cleaner versions of coal.

However, compared to burning coal directly, producing synfuels requires the mining of 50% more coal. Producing and burning synfuels could also add 50% more carbon dioxide to the atmosphere (Figure 15-17). As a result, synfuels have a lower net energy yield and cost more to produce per unit of energy than does coal production. Also, it takes large amounts of water to produce synfuels. Therefore, greatly increasing the use of these synfuels would worsen two of the world's major environmental problems: projected climate disruption caused mostly by CO_2 emissions and increasing water shortages in many parts of the world (see Figure 13-9, p. 324, and Figure 13-10, p. 324).

Figure 15-21 lists the advantages and disadvantages of using liquid and gaseous synfuels produced from coal (**Concept 15-4B**).

Figure 15-18 Coal sludge impoundment in West Virginia above an elementary school.



Jim West/Alamy

GREG GIRARD/National Geographic Creative

Figure 15-19 Coal ash from a power plant in China is dumped into an open landfill where it can be blown by wind and washed by precipitation onto surrounding lands.

Trade-Offs

Coal

Advantages	Disadvantages
Ample supplies in many countries	Severe land disturbance and water pollution
Medium to high net energy yield	Fine particle and toxic mercury emissions threaten human health
Low cost when environmental costs are not included	Emits large amounts of CO_2 and other air pollutants when produced and burned

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Figure 15-20 Using coal as an energy resource has advantages and disadvantages. ***Questions:*** Which single advantage and which single disadvantage do you think are the most important? Why? Do you think that the advantages of using coal as an energy resource outweigh its disadvantages? Explain.

Photo: El Greco/Shutterstock.com

Trade-Offs

Synthetic Fuels

Advantages	Disadvantages
Large potential supply in many countries	Low to medium net energy yield
Vehicle fuel	Requires mining 50% more coal with increased land disturbance, water pollution, and water use
Lower air pollution than coal	Higher CO_2 emissions than coal

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Figure 15-21 The use of synthetic natural gas (SNG) and liquid synfuels produced from coal as energy resources has advantages and disadvantages (Concept 15-2). ***Questions:*** Which single advantage and which single disadvantage do you think are the most important? Why? Do you think that the advantages of using synfuels produced from coal as an energy source outweigh the disadvantages? Explain.

Photo: ©mironov/Shutterstock.com

15-5 What Are the Advantages and Disadvantages of Using Nuclear Power?

CONCEPT 15-5

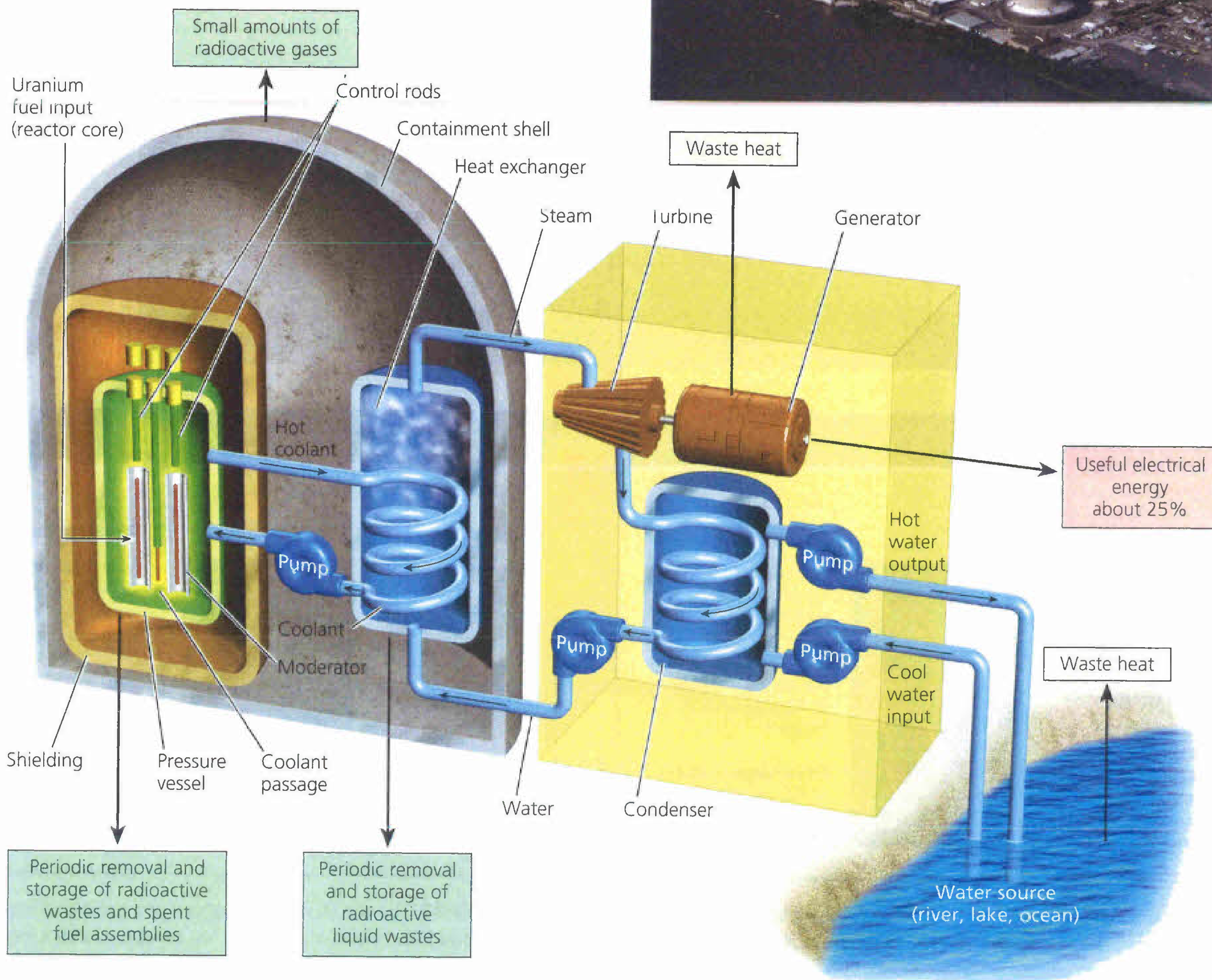
Nuclear power has a low environmental impact and a very low accident risk, but its use has been limited by a low net energy yield, high costs, fear of accidents, long-lived radioactive wastes, and its role in spreading nuclear weapons technology.

How Does a Nuclear Fission Reactor Work?

To evaluate the advantages and disadvantages of nuclear power, we must know how a nuclear power plant and its accompanying nuclear fuel cycle work. A nuclear power plant is a highly complex and costly system designed to perform a relatively simple task: to boil water and produce steam that spins a turbine and generates electricity.

Figure 15-22 This water-cooled nuclear power plant, with a pressurized water reactor, produces intense heat that is used to convert water to steam, which spins a turbine that generates electricity. ***Question:*** How does this plant differ from the coal-burning plant in Figure 15-15?

Robert Llewellyn/SuperStock



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What makes a nuclear power plant complex and costly is the use of a controlled nuclear fission reaction (see Figure 2-9, center, p. 40) to provide the heat. The fission reaction takes place in a *reactor.* The most common reactors, called light-water reactors (LWRs; see Figure 15-22), produce 85% of the world's nuclear-generated electricity (100% in the United States).

The fuel for a reactor is made from uranium ore mined from the earth's crust. After it is mined, the ore must be enriched to increase the concentration of its fissionable uranium-235 by 1–5%. The enriched uranium-235 is processed into small pellets of uranium dioxide. Each pellet, about the size of an eraser on a pencil, contains the energy equivalent of about a ton of coal. Large numbers of the pellets are packed into closed pipes, called *fuel rods,* which are then grouped together in *fuel assemblies,* to be placed in the core of a reactor.

Control rods are moved in and out of the reactor core to absorb neutrons generated in the fission reaction, thereby regulating the rate of fission and the amount of power produced. A *coolant,* usually water, circulates through the reactor's core to remove heat to keep the fuel rods and other reactor components from melting and releasing massive amounts of radioactivity into the environment. An LWR includes an emergency core cooling system as a backup to help prevent such meltdowns. A nuclear reactor cannot explode as an atomic bomb does and cause massive damage. The danger is from smaller explosions that can release radioactivity into the environment or cause a core meltdown.

Some nuclear plants withdraw the large quantities of cooling water they need from a nearby source such as a river or lake and return the heated water to that source. Other nuclear plants transfer the waste heat from the intensely hot water to the atmosphere by using one or more gigantic cooling towers, such as those at the Three Mile Island nuclear power plant near Harrisburg, Pennsylvania (USA), shown in the inset photo of Figure 15-22. There, a serious accident in 1979 caused a partial meltdown of one of the plant's reactors, but no lives were lost.

A *containment shell* with thick, steel-reinforced concrete walls surrounds the reactor core. It is designed to help keep radioactive materials from escaping into the environment, in case there is an internal explosion or a melting of the reactor's core. It also helps protect the core against some external threats such as tornadoes and plane crashes. These essential safety features help to explain why a new nuclear power plant costs as much as $10 billion and why that cost continues to rise.

What Is the Nuclear Fuel Cycle?

Building and running a nuclear power plant is only one part of the **nuclear fuel cycle** (Figure 15-23), which also includes the mining of uranium, processing and enriching the uranium to make fuel, using it in a reactor, safely storing the resulting highly radioactive wastes for thousands of years until their radioactivity falls to safe levels, and retiring the highly radioactive worn-out plant by taking it apart and storing its high- and moderate-level radioactive parts safely for thousands of years.

The final step in the cycle occurs when, after 20–60 years, a reactor comes to the end of its useful life, mostly because of corrosion and radiation damage to its metal parts, and it must be *decommissioned,* or retired. It cannot simply be shut down and abandoned, because its structure contains large quantities of high- and intermediate-level radioactive materials that must be kept out of the environment for thousands of years.

As long as a reactor is operating safely, the power plant itself has a fairly low environmental impact and a very low risk of an accident. However, considering the entire nuclear fuel cycle, the potential environmental impact increases. High-level radioactive wastes must be stored safely for thousands of years, and several points in the cycle are vulnerable to terrorist attack. Also, the uranium-enrichment and other technologies used in the cycle can be used to produce nuclear weapons–grade uranium (**Concept 15-5**).

Each step in the nuclear fuel cycle adds to the cost of nuclear power and reduces its net energy yield (**Concept 15-1**). If we add the enormous amount of energy needed to dismantle a plant at the end of its life and transport and safely store its highly radioactive materials, some scientists estimate that using nuclear power will eventually have a negative net energy yield, requiring more energy than it will ever produce.

Proponents of nuclear power tend to focus on the low CO_2 emissions and multiple safety features of the reactors. But in evaluating the safety, economic feasibility, net energy yield, and overall environmental impact of nuclear power, energy experts and economists caution us to look at the entire nuclear fuel cycle, not just the power plant itself. Figure 15-24 lists the major advantages and disadvantages of producing electricity by using the nuclear power fuel cycle (**Concept 15-3**).

Let's look more closely at some of the challenges involved in using nuclear power.

Storing Radioactive Spent-Fuel Rods Presents Risks

The high-grade uranium fuel in a nuclear reactor lasts for 3–4 years, after which it becomes *spent,* or useless, and must be replaced. On a regular basis, reactors are shut down for refueling, which usually involves replacing about a third of the reactor's fuel rods that contain the spent fuel.

The amount of nuclear waste from nuclear reactors is not huge, but the spent-fuel rods are so intensely hot and highly radioactive that they cannot be simply thrown away. Researchers have found that 10 years after being removed from a reactor, a single spent-fuel rod assembly can still emit enough radiation to kill a person standing 1 meter (39 inches) away in less than 3 minutes.

Thus, after spent-fuel rod assemblies are removed from reactors, they are stored in *water-filled pools* (Figure 15-25, left). After several years of cooling, they can be transferred to *dry casks* made of heat-resistant metal alloys and concrete and filled with inert helium gas (Figure 15-25, right). No one knows how long these casks can be used before they break down. They are licensed for 20 years and could last for 100 or more years—still a tiny fraction of the thousands of years that the waste must be safely stored.

A 2005 study by the U.S. National Academy of Sciences warned that the intensely radioactive waste storage pools and dry casks at 68 nuclear power plants in 31 U.S. states are especially vulnerable to sabotage or terrorist attack because they lie outside of the heavily protected reactor containment buildings. At each of the country's nuclear power plants, a government team of mock terrorists runs a test "attack" about every 3 years to test their security. Government records reveal that, between 2005 and 2010, eight of the roughly 100 attempts to breach security at U.S. nuclear plants were successful.

A 2002 study by the Institute for Resource and Security Studies and the Federation of American Scientists pointed out that in the United States, many millions of people live near aboveground spent-fuel storage sites. For some time, critics have been calling for the construction of much more secure structures to protect spent-fuel storage pools and dry casks and for moving more of the wastes from pools to casks. They charge that this has not been done because it would add billions of dollars to the already high cost of electricity produced by the nuclear power fuel cycle.

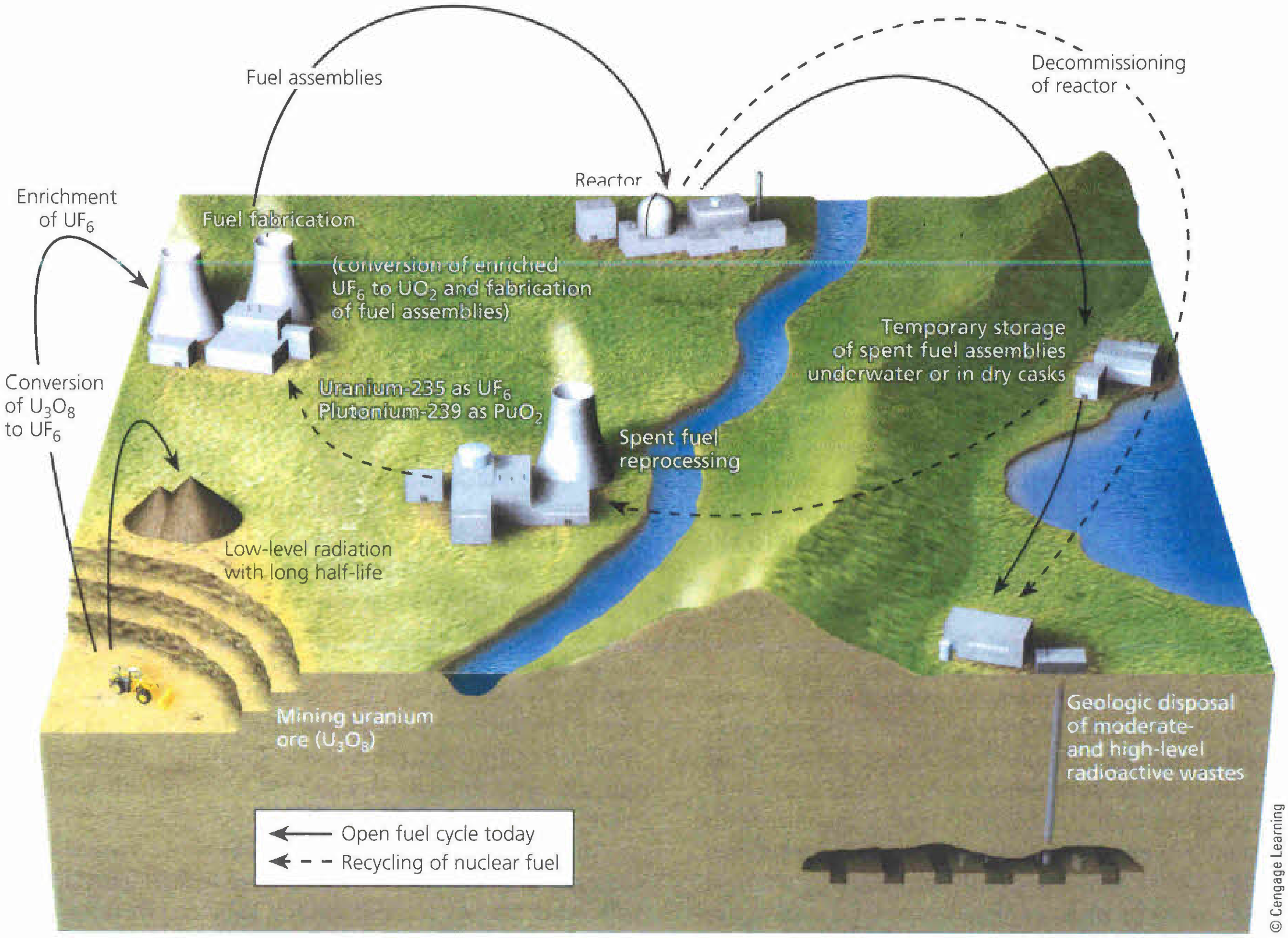
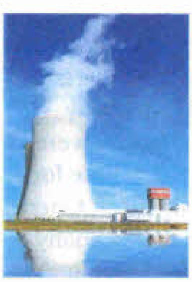


Figure 15-23 Using nuclear power to produce electricity involves a sequence of steps and technologies that together are called the *nuclear fuel cycle*. ***Question:*** Do you think the market price of nuclear-generated electricity should include all the costs of the nuclear fuel cycle, in keeping with the full-cost pricing **principle of sustainability**? (See Figure 1-5, p. 9 or back cover.) Explain.

Trade-Offs

Conventional Nuclear Fuel Cycle



Advantages	Disadvantages
Low environmental impact (without accidents)	Low net energy yield
	High overall cost
Emits 1/6 as much CO_2 as coal	Produces long-lived, harmful radioactive wastes
Low risk of accidents in modern plants	Promotes spread of nuclear weapons

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Figure 15-24 Using the nuclear power fuel cycle (Figure 15-23) to produce electricity has advantages and disadvantages. ***Questions:*** Which single advantage and which single disadvantage do you think are the most important? Why? Do you think that the advantages of using nuclear power outweigh its disadvantages? Explain.

Photo: ©Kletr/Shutterstock.com

CONSIDER THIS. . .

THINKING ABOUT Nuclear Waste Security

Do you favor measures to provide better protection for spent-fuel rods, even if they would raise the cost of electricity? Explain.

Dealing with Radioactive Nuclear Wastes Is a Difficult Scientific and Political Problem

The nuclear waste problem begins with spent-fuel rods. They can be processed to remove radioactive plutonium, which can then be used as nuclear fuel, thus closing the nuclear fuel cycle (Figure 15-23). This reprocessing reduces the storage time for the remaining wastes from up to 240,000 years (longer than the current version of the human species has been around) to about 10,000 years.

However, reprocessing is very costly, and the resulting plutonium could also be used by terrorists or nations to make nuclear weapons, as India did in 1974. This is mainly why the United States, after spending billions of dollars, abandoned this fuel recycling approach in 1977.

Figure 15-25 After 3 or 4 years in a reactor, spent-fuel rods are removed and stored in a deep pool of water contained in a steel-lined concrete basin (left) for cooling. After about 5 years of cooling, the fuel rods can be stored upright on concrete pads (right) in sealed dry-storage casks made of heat-resistant metal alloys and thick concrete. ***Questions:*** Would you be willing to live within a block or two of these casks or have them transported through the area where you live in the event that they were transferred to a long-term storage site? Explain. What are the alternatives?

Photos: U.S. Department of Energy/Nuclear Regulatory Commission

Also, a 2007 study by the nonprofit Institute for Energy and Environmental Research found that nuclear reprocessing increases the volume of nuclear waste sixfold and costs more than using mined uranium, further adding to the high cost of the nuclear fuel cycle. Currently, France, Russia, Japan, India, the United Kingdom, and China reprocess some of their nuclear fuel.

Some analysts have suggested that we could shoot our intensely radioactive wastes into space or into the sun. But the costs of such an effort would be extremely high and a launch accident—such as the 1986 explosion of the Space Shuttle Challenger—could disperse high-level radioactive wastes over large areas of the earth's surface.

Most scientists and engineers agree in principle that deep burial in an underground repository is the safest and cheapest way to store high-level radioactive wastes for thousands of years. Such repositories are in use on a limited basis in the U.S. state of New Mexico, for long-term storage of nuclear waste from the U.S. nuclear weapons program, and in Finland. However, some scientists contend that it is not possible to demonstrate that this or any method will work for thousands of years.

Between 1987 and 2009 the U.S. Department of Energy spent $12 billion on research and testing of a repository for long-term underground storage of high-level radioactive wastes from commercial nuclear reactors on federal land in the Yucca Mountain desert region northwest of Las Vegas, Nevada. In 2010, this project was abandoned for scientific and political reasons and because it was too small to store even the existing radioactive wastes. A government panel is looking for alternative solutions and sites, including two sites for temporary storage of dry casks. Meanwhile these deadly wastes are building up.

Some are calling for reviving the Yucca Mountain site process and for finding another underground storage site to handle future wastes. This presents a political problem, because most states do not want to host a nuclear waste repository, and most people do not want to have highly radioactive wastes transported through their communities on a regular basis from the country's various nuclear reactors (see the map in Figure 34, p. S59 in Supplement 6) to a central nuclear waste repository.

Another radioactive waste problem arises when a nuclear power plant reaches the end of its useful life after about 40 to 60 years and must be closed. Around the world, 285 of the 432 commercial nuclear reactors now operating will need to be decommissioned by 2025.

Eventually all nuclear plants will have to be dismantled and their high-level radioactive materials will have to be stored safely. Scientists have proposed three ways to do this. For any particular plant, one strategy is to store the highly radioactive parts in a permanent, secure repository. A second approach is to install a physical barrier around the plant and set up full-time security for 30–100 years, until the plant can be dismantled after its radioactivity has reached safer levels. These levels would still be high enough to require long-term safe storage of leftover materials.

A third option is to enclose the entire plant in a concrete and steel–reinforced tomb, called a containment structure. This is what was done with a reactor at Chernobyl, Ukraine, that exploded and nearly melted down in 1986, due to a combination of poor reactor design and human operator error. The explosion and the radiation released over a large area killed a number of people and contaminated a vast area of land with long-lasting radioactive fallout in what is viewed as the world's worst nuclear power plant accident. However, within a few years, the containment structure began to crumble, due to the corrosive nature of the radiation inside the damaged reactor, and to leak radioactive wastes. The structure is being rebuilt at great cost and is unlikely to last even several hundred years.

Regardless of the method chosen, the high costs of retiring nuclear plants add to the enormous costs of the nuclear power fuel cycle and reduce its already low net energy yield. Even if all the nuclear power plants in the world were shut down tomorrow, we would still have to find a way to protect ourselves from their high-level radioactive components for thousands of years.

Can Nuclear Power Lessen Dependence on Imported Oil and Help Reduce Projected Climate Change?

Some proponents of nuclear power in the United States claim it will help the country to reduce its dependence on imported crude oil. Other analysts argue that because oil-burning power plants provide only about 1% of the electricity produced in the United States and similarly small amounts in most other countries that use nuclear power, replacing these plants with very costly nuclear power plants would not save much oil.

Nuclear power advocates also contend that increased use of nuclear power will greatly reduce the CO_2 emissions that contribute to projected climate change. Critics argue that the nuclear power industry has mounted a misleading but effective public relations campaign to convince the public that nuclear power does not emit CO_2 and other greenhouse gases.

As scientists point out, this argument is only partially correct. While nuclear plants are operating, they do not emit CO_2. However, during the 10 years that it typically takes to build a plant, especially in the manufacturing of many tons of construction cement, large amounts of CO_2 are emitted. Every other step in the nuclear power fuel cycle (Figure 15-23) also involves CO_2 emissions. Such emissions are much lower than those from coal-burning power plants (Figure 15-17), but they still contribute to atmospheric warming and projected climate disruption.

In 2009, Michael Mariotte, Executive Director of the Nuclear Information and Resource Service, estimated that in order for nuclear power to play an effective role in slowing projected climate disruption over the next 50 years, the world would need to build some 2,000 nuclear reactors—an average of one about every 2 weeks. If power plants could be brought online at such a pace, the amount of high-level radioactive wastes generated would grow dramatically. This would require that new and very costly nuclear waste repositories be built at a similar fast pace.

Experts Disagree about the Future of Nuclear Power

In the 1950s, researchers predicted that by the year 2000, at least 1,800 nuclear power plants would supply 21% of the world's commercial energy (25% of that in the United States) and most of the world's electricity. After almost 60 years of development, a huge financial investment, and enormous government subsidies, some 432 commercial nuclear reactors in 31 countries produced only 5% of the world's commercial energy and 15% of its electricity. In the United States, 104 licensed commercial nuclear power reactors generate about 8% of the country's overall energy and 19% of its electricity.

In 2013, 60 new nuclear reactors were under construction in 13 countries, far from the number needed just to replace the reactors that will have to be decommissioned in coming years. Another 156 reactors are planned, but even if they are completed after a decade or two, they will not replace the 285 aging reactors that must be retired around the world. This helps to explain why nuclear power is now the world's slowest-growing form of commercial energy (see Figure 8, p. S67, in Supplement 7).

The future of nuclear power is a subject of debate. Critics argue that the most serious problem with the nuclear power fuel cycle is that it is uneconomical. They contend that the nuclear power industry could not exist without high levels of financial support from governments and taxpayers, because of the extraordinarily high cost of ensuring safety and the low net energy yield of the nuclear power fuel cycle.

For example, the U.S. government has provided huge research and development subsidies, tax breaks, and loan guarantees to the industry (with taxpayers accepting the risk of any debt defaults) for more than 50 years. It also assumes most of the financial burden of finding ways to store radioactive wastes. In addition, the government provides accident insurance guarantees, because insurance companies have refused to fully insure any nuclear reactor from the consequences of a catastrophic accident. Nuclear power is the only energy resource that receives this government subsidy.

According to the nonpartisan Congressional Research Service, since 1948, the U.S. government has spent more than $95 billion (in 2011 dollars) on nuclear energy research and development (R & D)—more than 4 times the amount spent on R & D for solar, wind, geothermal, biomass, biofuels, and hydropower combined. Critics contend that, without these large and little-known subsidies and tax breaks, the nuclear industry would not exist in the United States. Some question the need for continuing such taxpayer support.

CONSIDER THIS. . .

THINKING ABOUT Government Subsidies for Nuclear Power

Do you think the benefits of nuclear power justify high government (taxpayer) subsidies and tax breaks for the nuclear industry? Explain.

Another obstacle to the growth of nuclear power has been public concerns about the safety of nuclear reactors. Because of the multiple built-in safety features, the risk of exposure to radioactivity from nuclear power plants in the United States and most other more-developed countries is extremely low. However, several explosions and partial or complete meltdowns have occurred (see the Case Study that follows).

CONSIDER THIS. . .

CONNECTIONS Nuclear Power Plants and the Spread of Nuclear Weapons

In the international marketplace, the United States and 14 other countries have been selling commercial and experimental nuclear reactors and uranium fuel-enrichment and purification technology for decades. Much of this information and equipment can be used to produce nuclear weapons. Energy expert John Holdren pointed out that 60 countries that have nuclear weapons or the knowledge to develop them (not including the United States, Great Britain, and the former Soviet Union) have gained most of such information by using civilian nuclear power technology. Some critics see this as the single most important reason for not building more nuclear power plants anywhere in the world.

Proponents of nuclear power argue that governments should continue funding research, development, and pilot-plant testing of potentially safer and less costly new types of reactors. The nuclear industry claims that hundreds of new *advanced light-water reactors (ALWRs)* could be built in just a few years. ALWRs have built-in safety features designed to make meltdowns and releases of radioactive emissions almost impossible. Another proposal is to mix beryllium and uranium to create fuel rods for conventional reactors that would help to prevent meltdowns.

In 2012, the U.S. Nuclear Regulatory Commission approved construction of two new nuclear reactors at an existing power plant in Georgia. Each will have a passive cooling system that can slowly cool the core and prevent a meltdown without the use of pumps when the system has to be shut down. These reactors are being built with the help of loan guarantees from the federal government. Also, the state of Georgia gave permission to the electric utilities to pre-charge their customers for the costs of building these reactors even if they are never completed. Also in 2012, the Department of Energy provided research and development funds for the development and evaluation of small modular reactors that would be built at a factory, hauled to a plant site by train, truck, or barge, placed underground, and wired up.

Some scientists call for replacing today's uranium-based reactors with new ones to be fueled by thorium. They argue that such reactors would be much less costly and safer because they cannot melt down. Also, the nuclear waste they produce cannot be used to make nuclear weapons. To help reduce its dependence on coal, China, which gets less than 2% of its electricity from nuclear power, is building 26 nuclear power plants, some of them fueled with thorium. China is also building a repository for high-level nuclear waste in the country's arid west.

To be environmentally and economically acceptable, some analysts believe that any new-generation nuclear technology should meet the five criteria listed in Figure 15-26. So far, no existing or proposed reactors even come close to doing so. However, even with considerable government financial support and loan guarantees, most U.S. utility companies and money lenders are unlikely to take on the financial risk of building new nuclear plants of any design, as long as electricity can be produced more cheaply with the use of natural gas (**Core Case Study**) and wind power.

CASE STUDY

The 2011 Nuclear Power Plant Accident in Japan

A major accident occurred on March 11, 2011, at the Fukushima Daiichi Nuclear Power Plant on the northeast coast of Japan. The accident was triggered by a major offshore earthquake that caused a severe tsunami (see Figure 14-22, p. 368). A huge wave of seawater washed over the nuclear plant's protective seawalls and knocked out the circuits and backup diesel generators of the emergency core cooling systems for three of the reactors. Then, explosions (presumably from the buildup of hydrogen gas) blew the roofs off three of the reactor buildings (Figure 15-27) and released radioactivity into the atmosphere and nearby coastal waters. Evidence indicates that the cores of these three reactors suffered full meltdowns.

After some initial confusion and conflicting statements about the severity of the accident, the Japanese government evacuated all residents within a 20-kilometer (12-mile) radius of the plant. Two weeks later, as the severity of the accident became more apparent, people within 30 kilometers (19 miles) were urged to evacuate. More than 110,000 people left their homes, and some areas that now still contain high radiation levels will likely remain unsafe to occupy for up to 20 years.

Preliminary studies indicate that four key human-related factors contributed to this accident: **(1)** failure of the utility company to develop worst-case scenarios that

Solutions

- Reactors must be built so that a runaway chain reaction is impossible.
- The reactor fuel and methods of fuel enrichment and fuel reprocessing must be such that they cannot be used to make nuclear weapons.
- Spent fuel and dismantled structures must be easy to dispose of without burdening future generations with harmful radioactive waste.
- Taking its entire fuel cycle into account, nuclear power must generate a net energy yield high enough so that it does not need government subsidies, tax breaks, or loan guarantees to compete in the open marketplace.
- Its entire fuel cycle must generate fewer greenhouse gas emissions than other energy alternatives.

Figure 15-26 Some critics of nuclear power say that any new generation of nuclear power plants should meet all of these five criteria. ***Question:*** Do you agree or disagree with these critics? Explain.

would have helped speed up their reaction to the crisis, **(2)** the fact that the plant's protective seawalls were not built high enough to withstand huge tsunami waves in this well-known earthquake zone, **(3)** design flaws that exposed the emergency core cooling system controls and backup generators to flooding and that failed to protect the spent-fuel rod storage pools from the damages they suffered, and **(4)** a too-cozy relationship between nuclear plant owners' and the government's nuclear regulatory officials.

This accident and the flawed response to it on the parts of plant officials and the government greatly damaged the public confidence of Japanese citizens in the safety of nuclear power. It was a serious accident that contaminated a large area with low to moderate levels of radioactivity. Over the long term, this radiation is projected to kill from 100 to 1,500 people by causing cancers, especially thyroid cancer.

This accident could lead to reduced reliance on nuclear power in Japan. It has prompted Germany, Switzerland, and Belgium to announce plans for phasing out nuclear power. Nuclear power proponents see this as an overreaction, arguing that the annual death toll resulting from the burning of coal is much greater than that of nuclear power accidents.

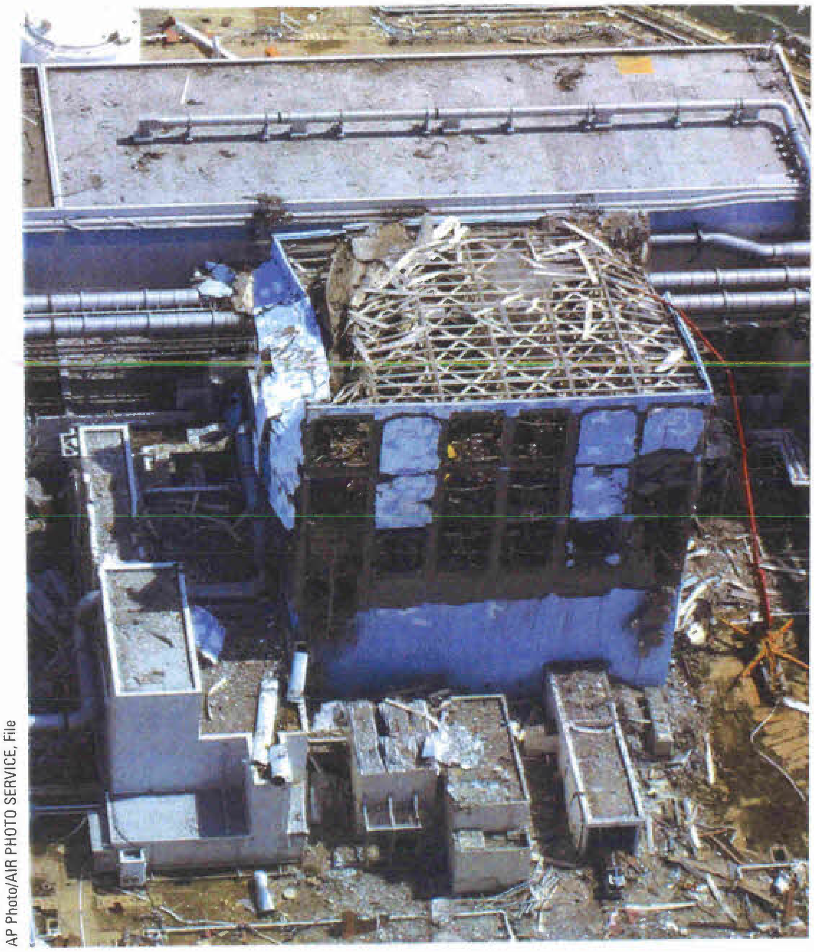
AP Photo/AIR PHOTO SERVICE, File

Figure 15-27 An explosion in one of the reactors in the Fukushima Daiichi nuclear power plant severely damaged the reactor.

Is Nuclear Fusion the Answer?

Other proponents of nuclear power hope to develop **nuclear fusion**—a nuclear change at the atomic level in which the nuclei of two isotopes of a light element such as hydrogen are forced together at extremely high temperatures until they fuse to form a heavier nucleus, releasing energy in the process (see Figure 2-9, bottom, p. 40). Some scientists hope that controlled nuclear fusion will provide an almost limitless source of energy.

With nuclear fusion, there would be no risk of a meltdown or of a release of large amounts of radioactive materials, and little risk of the additional spread of nuclear weapons. Fusion power might also be used to destroy toxic wastes and to supply electricity for desalinating water and for decomposing water to produce hydrogen fuel as a very clean-burning energy source.

However, in the United States, after more than 50 years of research and a $25 billion investment, controlled nuclear fusion is still in the laboratory stage. None of the approaches tested so far has produced more energy than they use. In 2006, the United States, China, Russia, Japan, South Korea, India, and the European Union agreed to spend at least $12.8 billion in a joint effort to build a large-scale experimental nuclear fusion reactor by 2026 to determine if it can produce a net energy yield. By 2012, the estimated cost of this project had doubled and it was behind schedule.

If everything goes well, the experimental fusion reactor is supposed to produce enough electricity to run the air conditioners in a small city for a few minutes. Some critics view it as a very costly pie-in-the-sky project that diverts money from more promising energy alternatives like wind and solar energy. Unless there is an unexpected scientific breakthrough, some skeptics will continue to quip that "nuclear fusion is the power of the future and always will be."

Big Ideas

- A key factor to consider in evaluating the long-term usefulness of any energy resource is its net energy yield.
- Conventional oil, natural gas, and coal are plentiful and have moderate to high net energy yields, but use of these fossil fuels, especially coal, has a high environmental impact.
- The nuclear power fuel cycle has a low environmental impact and a very low accident risk, but high costs, a low net energy yield, long-lived radioactive wastes, and its role in spreading nuclear weapons technology have limited its use.

TYING IT ALL TOGETHER A New U.S. Oil and Natural Gas Era and Sustainability


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We began this chapter with a look at the possibility of a new era of oil and natural gas production in the United States. We also learned a guiding scientific principle underlying all energy use—that the long-term usefulness of any energy resource depends on its *net energy yield.* Conventional oil, natural gas, and coal have medium to high net energy yields that will decrease as we use up their easily accessible supplies. Using these energy resources and others derived from them involves high environmental impacts, although these impacts vary. For example, using coal has a very high environmental impact (see photo at left and chapter-opening photo), compared to use of oil and natural gas. Implementing regulations to reduce these harmful environmental impacts will further reduce the net energy yields of these fuels.

We also looked at how we use nuclear power to produce electricity. As we evaluate the net energy yield and environmental impacts of nuclear power, it is important to consider the whole cradle-to-grave nuclear power fuel cycle—from mining the uranium fuel to dismantling and storing the worn-out reactor parts for thousands of years. Considering this whole fuel cycle, nuclear power's environmental impacts are fairly high, and its net energy yield is so low that it is economically unsustainable and must be propped up by various subsidies.

We cannot recycle energy because of the second law of thermodynamics (see Chapter 2, p. 43). However, by reusing and recycling more of the materials we use in our daily lives and in industry and transportation, we could cut our need for energy, thereby raising net energy yields—an application of the chemical cycling **principle of sustainability** (see Figure 1-2, p. 6 or back cover). Also, by using a diversity of energy resources, just as nature relies on the biodiversity **principle of sustainability**, we can further reduce the environmental impacts of our use of energy. Applying the full-cost pricing **principle of sustainability** (see Figure 1-5, p. 9 or back cover) to all energy resources would give us a more realistic understanding of the true economic and environmental costs of using nonrenewable fossils fuels and nuclear power, as well as a variety of renewable energy alternatives that we examine in the next chapter.

Chapter Review

Core Case Study

1. Summarize the potential for greatly increased production of oil and natural gas in the United States and describe two major problems to be overcome.

Section 15-1

2. What is the key concept for this section? What is **net energy yield** and why is it important in evaluating energy resources? Explain why some energy resources need help in the form of subsidies to compete in the marketplace, and give an example.

Section 15-2

3. What are the two key concepts for this section? What is **crude oil (petroleum)**, and how are oil deposits detected and removed? What percentages of the commercial energy used in the world and in the United States are provided by conventional crude oil? What is the **peak production** for an oil well and for the world oil deposits? What is **refining**? What are **petrochemicals** and why are such chemicals important? What countries are the world's three largest producers of oil and what countries are the three largest consumers?

4. What are **proven oil reserves** and what five factors determine such reserves? Define **horizontal drilling** and **hydraulic fracturing** or **fracking** and explain how these two technologies are being used to extract tightly held oil and natural gas from shale rock. What three countries have the largest percentages of the world's proven oil reserves? What percentages are found in the United States and China? Based on data from the U.S. Department of Energy and the U.S. Geological Survey, what are three conclusions that have been drawn concerning consumption of conven-

tional light oil? What are the major environmental costs of using oil? What are the major advantages and disadvantages of using conventional light oil as an energy resource? Describe U.S. dependence on oil and on imported oil. How can U.S. oil production increase dramatically in coming years, according to some analysts? What are two factors that could limit such an increase in domestic oil production?

5. Explain how we can get heavy oil from oil shale rock and from **tar sands (oil sands)**. What are the major advantages and disadvantages of using heavy oils produced from tar sands and from oil shale rock?

Section 5-3

6. What is the key concept for this section? Define **natural gas**, **liquefied petroleum gas (LPG)**, and **liquefied natural gas (LNG)**. What countries have the three largest portions of the world's proven natural gas reserves? What percentages of the world's reserves are held by the United States and China? What are the major advantages and disadvantages of using conventional natural gas as an energy resource? Why has natural gas production risen sharply in the United States and what two factors could hinder this rise? Describe five major problems resulting from increased use of fracking to produce natural gas in the United States and six ways to deal with these problems. What are two other sources of unconventional natural gas and what major problems are related to the use of these resources?

Section 15-4

7. What are the two key concepts for this section? What is **coal** and how is it formed? How does a coal-burning power plant work? What percentage of the electricity used in the world and in the United States comes from burning coal in power plants? What three countries have the largest proven reserves of coal? What are three major problems resulting from the use of coal? Explain why there is no such thing as clean coal. What are the major advantages and disadvantages of using coal as an energy resource? What are the major advantages and disadvantages of using **synthetic natural gas (SNG)** produced from coal?

Section 15-5

8. What is the key concept for this section? How does a nuclear fission reactor work and what are its major safety features? Describe the **nuclear fuel cycle**. What are three ways to decommission a nuclear power plant at the end of its useful life? What are the major advantages and disadvantages of relying on the nuclear fuel cycle as a way to produce electricity? How do nuclear plant operators store highly radioactive spent-fuel rods? Why is dealing with the highly radioactive wastes produced by the nuclear fuel cycle such a difficult problem? Explain why nuclear power is not likely to reduce U.S. dependence on imported oil and why it is not likely to reduce projected climate disruption.

9. Compare the projections for growth of the nuclear industry in the 1950s with its actual role now in generating electricity. What is the role of government subsidies in nuclear power? List and explain three major factors that have kept nuclear power from growing. What is the connection between commercial nuclear power plants and the spread of nuclear weapons? Describe the 2011 nuclear power plant accident in Japan. Define **nuclear fusion**, and summarize the story of attempts to develop it as an energy resource.

10. What are this chapter's *three big ideas*? Explain how the chemical cycling, biodiversity, and full-cost pricing **principles of sustainability** (see Figure 1-2, p. 6, and Figure 1-5, p. 9, or back cover) could be applied to our future energy resource choices.

Note: Key terms are in bold type.

Critical Thinking

1. How might greatly increased production of domestic oil and natural gas in the United States over the next two decades (**Core Case Study**) affect the country's future use of coal, nuclear power, and energy from the sun and wind? How might such an increase affect your life during the next 20 years?

2. Should governments give a high priority to net energy yields when deciding what energy resources to support? What are other factors that should be considered? Explain your thinking.

3. To continue using conventional oil at the current rate, we must discover and add to global oil reserves the equivalent of one new Saudi Arabian reserve every 7 years. Do you think this is possible? If not, what effects might the failure to find such supplies have on your life and on the lives of any child and grandchild that you might have?

4. List three steps you could take to reduce your dependence on oil and gasoline. Which of these things do you already do or plan to do?

5. Some people see imports of Canadian oil produced from tar sands as a way to reduce U.S. dependence on oil imports from potentially unstable Middle Eastern countries and from Venezuela. Others call for developing unconventional oil from shale rock (Science Focus 15.1) as a domestic resource in order to reduce U.S. oil imports. Still others oppose both of these options because they involve environmentally