CHAPTER
12
Nonrenewable Energy Resources
An oil refinery in Antwerp, Belgium
All Energy Use Has Consequences

A series of pivotal moments in the 1960s led to the first Earth Day in 1970. One of those events was an oil well explosion and rupture—called a blowout—off the coast of Santa Barbara, California, in January 1969. Before the resulting spill was contained, over 11.4 million liters (3 million gallons) of crude oil poured into the Santa Barbara Channel. Some of it washed ashore, coating sandy beaches and marine life with oil. The spill drew national attention—oil-soaked birds that were unable to fly were featured in newspapers and on the evening news. And yet, despite repeated warnings that we are addicted to oil, our reliance on oil and other fossil fuels has only increased.

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Subsequent oil spills all over the world, on land and in water, have attracted national and international attention. Some spills have been caused by leaks or explosions where the oil was being extracted from the ground. Others have occurred while the oil was being transported by pipeline or tanker. In March 1989, the Exxon Valdez, a supertanker carrying 200 million liters (53 million gallons) of oil, crashed into a reef in Prince William Sound, Alaska. Roughly 42 million liters (11 million gallons) of oil spilled into the sound. Much of it washed up on shore, coating the coastline and killing hundreds of thousands of birds and thousands of marine mammals. This spill was the largest in U.S. waters for 21 years, until a blowout occurred at the BP Deepwater Horizon oil well in the Gulf of Mexico in April 2010. (BP used to be known as British Petroleum.) That accident killed 11 workers on the drilling platform, injured 17 others, and led to the release of well over 780 million liters (206 million gallons) of oil. This oil has dispersed in the Gulf of Mexico and washed up on the shores of Louisiana, Texas, Mississippi, Alabama, and Florida.

Even after oil is safely extracted from underground and transported to a refinery, accidents can occur. In 2005, 15 workers died in an explosion at a BP oil refinery in Texas. Nor do the hazards of fossil fuel use end with production. After the oil that is refined into gasoline, jet fuel, or diesel reaches its end use location, and is burned to run a vehicle or heat a house, the combustion process emits pollutants, which cause a number of environmental problems.
Other fossil fuels pose similar risks. In April 2010, an explosion in a coal mine in West Virginia killed 29 coal miners. This explosion was the worst coal mine disaster in the United States in 40 years, but only a century earlier, in the early 1900s, there were hundreds of accidental mining deaths per year in the United States. And long after they leave the mines, hundreds of thousands of coal miners develop black lung disease and other respiratory ailments that lead to disability or death.

Natural gas is considered to be the “clean” fossil fuel. Emissions of particulates, sulfur dioxide, and carbon dioxide are lower per unit energy obtained from natural gas than from oil or coal. But the extraction of natural gas has its consequences too. Exploration and extraction take place in many different locations on land and under water. “Thumper trucks,” which generate seismic vibrations in order to identify natural gas deposits underground, can disturb soil and alter groundwater flow, causing certain areas to flood and wells to go dry. Drilling and the use of water for gas extraction can cause contamination of groundwater. Once extracted, natural gas requires pipelines to transport it. Construction of pipelines is disruptive to the environment, and communities often oppose such construction.

The United States is dependent on fossil fuels for our energy supply. We are faced with constant reminders of that dependence and of the adverse consequences of using fossil fuels. Obviously, many of the benefits of our modern society—health care, comfortable living conditions, easy travel, plentiful food—come from our use of readily accessible and relatively affordable fossil fuels—but not without long-term costs.

Sources: J. Goodell, Big Coal (Mariner Books, 2007); L. Margonelli, Oil on the Brain (Broadway Books, 2008).

Key Ideas
We use energy in all aspects of our daily lives: heating and cooling, cooking, lighting, communications, and travel. In these activities, humans convert energy resources such as natural gas and oil into useful forms of energy such as motion, heat, and electricity, with varying degrees of efficiency and environmental effects. We learned the fundamental energy concepts underlying these conversions in Chapter 2. This chapter focuses on conventional, nonrenewable energy resources—coal, oil, natural gas, and nuclear fuels.

After reading this chapter you should be able to
- describe how energy use and energy resources have varied over time, both in the United States and worldwide.
- compare the energy efficiencies of the extraction and conversion of different fuels.
- explain the various means of generating electricity.
- discuss the uses and consequences of using coal, oil, natural gas, and nuclear fuels.
- describe projections of future supplies of our conventional energy resources.

12.1 Nonrenewable energy accounts for most of our energy use

Each energy choice we make has positive and negative consequences. In a society like the United States, where each person averages 10,000 watts of energy use continuously—24 hours per day, 365 days per year—this means there are a lot of consequences to understand, evaluate, and possibly try to change. In this chapter we will look at the fossil fuel and nuclear fuel supplies that we currently use. These types of energy resources are often called nonrenewable because, like the mineral resources we discussed in Chapter 8, once they are used up, they cannot be replenished. In other words, the supplies of these energy types are finite. Chapter 13 addresses the renewable energy resources that we use to some extent now and that many people expect we will use even more in the future.

The two primary categories of nonrenewable energy resources are fossil fuels and nuclear fuels. Fossil fuels are derived from biological material that became fossilized millions of years ago. Coal, oil, and natural gas are the three major fossil fuels. To access the ancient solar energy contained in the chemical bonds of fossil fuels, we burn those fuels and harness the heat energy from their combustion. Nuclear fuels are derived from radioactive materials that give off energy. We harness that energy by transferring heat as well.

We will begin our examination of conventional energy resources by looking at patterns of energy use in the world and in the United States.
12.1. Worldwide Patterns of Energy Use

Every country in the world uses energy at different rates and relies on different energy resources. Factors that determine the rate at which energy is used include which resources are available and affordable. In the past few decades, environmental impacts have also come to play a part in some energy use decisions.

In order to talk about quantities of energy used, it is helpful to use specific measures. Recall from Chapter 2 that the basic unit of energy is the joule (J). A gigajoule (GJ) is 1 billion \((1 \times 10^9)\) joules, or about as much energy as is contained in 30 L (8 gallons) of gasoline. An exajoule (EJ) is 1 billion \((1 \times 10^9)\) gigajoules. In some figures, we also present the unit of energy that the U.S. government uses for reporting energy consumption. That unit, not used anywhere other than in the United States, is the quad, which is 1 quadrillion, or \(1 \times 10^{15}\), Btu. One quad is equal to 1.055 EJ.

As Figure 12.1 shows, in 2008, total world energy consumption was approximately 495 EJ per year. This number amounts to roughly 75 GJ per person per year. Oil, coal, and natural gas were the three largest energy sources. Peat, a precursor to coal, is sometimes combined with coal for reporting purposes in certain countries, mostly in the developing world.

**Figure 12.1** Annual energy consumption worldwide by resource. Oil, coal and peat, and natural gas are the major sources of energy for the world. [Data from the International Energy Agency, 2009.]
Energy use is not evenly distributed throughout the world, however, as **Figure 12.2** shows. Energy consumption in the United States was 355 GJ per person per year in 2007, almost 5 times greater than the world average. In fact, although only 20 percent of the world’s population lives in developed countries, those people use 70 percent of the world’s energy each year. Note that of
the countries shown in FIGURE 12.2, the United States has the greatest total energy consumption, whereas Canada has the greatest per capita energy consumption. At 0.12 EJ per year, Tanzania has the lowest annual energy consumption of the countries shown; annual per capita energy consumption in Tanzania is 2.85 GJ per person per year.

There are a variety of reasons for the patterns we see in FIGURE 12.2. In developed countries and in urban areas of some developing countries, individuals are likely to use fossil fuels such as coal, oil, and natural gas—either directly or indirectly through the use of electricity generated by burning those fuels. However, people living in rural areas of developing countries still primarily use fuels such as wood, charcoal, or animal waste, in addition to proportionately larger amounts of human and animal energy. Accordingly, we can distinguish between commercial and subsistence energy sources. Commercial energy sources are those that are bought and sold, such as coal, oil, and natural gas. Sometimes wood, charcoal, and animal waste are also sold commercially. Subsistence energy sources are those gathered by individuals for their own immediate needs. There is much greater use of subsistence energy sources in the developing world, especially in rural areas.

Changes in energy demand generally reflect the level of industrialization that is occurring in a country or region. As energy demand increases, societies change the types of fuels they use. Today, we see the same patterns of changing energy use in developing countries that have been observed historically in the United States. For example, as more people own automobiles, demand for gasoline and diesel increases. As industries develop and factories are built, demand for electricity and nuclear fuels increases. Although worldwide energy use varies considerably, the United States is a particularly large energy consumer, so we will focus on energy use in the United States for much of this chapter.

12.1. Patterns of Energy Use in the United States

FIGURE 12.3 shows the history of energy use in the United States. Wood was the predominant energy source until about 1875, when coal came into wider use. Starting in the early 1900s, oil and natural gas joined coal as the primary sources of energy. By 1950, electricity generated by nuclear energy became part of the mix, and hydroelectricity became more prominent. The 1970s saw a decline of oil and a resurgence of coal. These changes were the result of political, economic, and environmental factors that will continue to shape energy use into the future. Today, the three resources that supply the majority of the energy used in the United States and worldwide—in order of increasing importance—are oil, coal, and natural gas.
We can consider energy use in the United States today as the inputs and outputs of an enormous system (FIGURE 12.4). The boundaries of the system are social and technological as well as physical. For example, oil inputs enter the U.S. energy system both from domestic production and from other countries. Hydroelectric energy comes from water that flows within the physical boundaries of the country, as well as from neighboring Canada, but it is not an energy input until we move it into a technological system, such as a hydroelectric dam. One major output from the system is work—the end use of the energy, such as transportation or industry. The other major output is waste: heat, CO₂, and other pollutants that are released as energy is converted and entropy increases.

Figure 12.3  Energy consumption in the United States since 1850. Wood and then coal used to dominate our energy supply. Today a mix of three fossil fuels accounts for much of our energy use. [After U.S. Department of Energy, Energy Information Administration, 2008.]
Figure 12.4  Energy inputs and outputs in the United States. (a) The types of fuels that are used are shown on the left, and their end uses are shown on the right. (Sums may differ by one whole unit due to rounding.) (b) Energy consumption by fuel type. [(a) After U.S. Department of Energy,
In 2008, U.S. energy input was approximately 105 exajoules (1.05 × 10^{18} J) per year. The energy mix of our input is 84 percent fossil fuel, 9 percent nuclear fuel, and 7 percent renewable energy resources. The United States produces 70 percent of the energy it needs. Nearly 30 percent of our energy comes from other countries, primarily in the form of petroleum imports. Industry uses the most energy, followed by the transportation sector.

Energy use varies regionally and seasonally. In the midwestern and southeastern states, coal is the primary fuel burned for electricity generation. The western and northeastern states generate electricity using a mix of nuclear fuels, natural gas, and hydroelectric dams. Highly populated areas tend to use less coal, which creates the most air pollution of any fuel. Northern areas consume more oil and natural gas during the winter months to meet the demand for heating. Southern areas consume more electricity in the summer months to meet air conditioning needs.

The type of energy that is used for a particular application is a function of many factors, including the features that each type of energy offers. Those features include ease of transportation and the amount of energy a given mass of fuel contains.

### 12.1. Energy Types and Quality

Imagine running your car on coal or firewood. In order to run your car with one of these fuels and travel the same distance as a conventional car on one tank of gasoline, you would have to carry around a larger volume of material. Gasoline, the current fuel of choice for personal transportation, gets you a lot farther on a much smaller volume. This thought experiment highlights the importance of considering energy type and quality.

Certain forms of energy are best suited for particular purposes. For example, for transportation, we usually prefer gasoline or diesel—liquid energy sources that are relatively compact, meaning that they have a high energy-to-mass ratio. Energy-to-mass ratio is not the only consideration for fuel choice, however. A wood or coal fire starts relatively slowly. Gasoline and diesel are also ideal fuels for vehicles because of the speed with which they can provide or cut off the energy supply. Unfortunately, compared with other energy sources, such as natural gas or hydroelectricity, gasoline produces large amounts of air pollution per joule of energy released. In addition, gasoline requires a good deal of refining—chemical processing—to produce, unlike coal or wood.
QUANTIFYING ENERGY EFFICIENCY Although all conventional nonrenewable energy sources have environmental impacts, clearly some are better suited for particular jobs than others. One of the ways we can determine the best source to use is to consider energy efficiency: both the efficiency of the process of obtaining the fuel and the efficiency of the process that converts it into the work that is needed. Thus we can evaluate how effectively we use energy by quantifying both the energy expended to obtain a fuel and how efficiently we use it.

In Chapter 2 we discussed energy efficiency as well as energy quality, a measure of the ease with which stored energy can be converted into useful work. The second law of thermodynamics dictates that when energy is transformed, its ability to do work diminishes; some energy is lost during each conversion. In addition to these losses, for almost every fuel that we use, there is an energy expenditure involved in obtaining the fuel.

FIGURE 12.5 outlines the process of energy use from extraction of a resource to electricity generation and disposal of waste products from the power plant. As we can see from the red arrows in the figure, there are many opportunities for energy loss, each of which reduces energy efficiency. You may recall from FIGURE 2.15 that the efficiency of converting coal into electricity is approximately 35 percent. In other words, about two-thirds of the energy that enters a coal-burning electricity generation plant ends up as waste heat or other undesired outputs. If we included the energy used to extract the coal, and if we included the energy used to build the coal extraction machinery, to construct the power plant, and to remove and dispose of the waste material from the power plant, the efficiency of the process would be even lower. All of these other energy inputs are called embodied energy, and they will be discussed in greater detail in Chapter 16.
Every energy source, from coal to oil to wind, requires an expenditure of energy to obtain it. The most direct way to account for the energy required to produce a fuel, or energy source, is to calculate the energy return on energy investment (EROEI), or how much energy we get out of an energy source for every unit of energy expended on its production. EROEI is calculated as follows:

\[
\text{EROEI} = \frac{\text{Energy obtained from the fuel}}{\text{Energy invested to obtain the fuel}}
\]

For example, in order to obtain 100 J of coal from a surface coal mine, 5 J of energy is expended. Therefore,

\[
\text{EROEI} = \frac{100 \text{ J}}{5 \text{ J}} = 20
\]

As you might expect, a larger value for EROEI suggests a more efficient and more desirable process. The Science Applied section that follows Chapter 13, “Should Corn Become Fuel?” calculates the EROEI for ethanol, a fuel made from corn.
FINDING THE RIGHT ENERGY SOURCE FOR THE JOB

When deciding between two energy sources for a given job, it is essential to consider the overall system efficiency. Sometimes the trade-offs are not immediately apparent. The home hot water heater is an excellent illustration of this principle.

Electric hot water heaters are often described as being highly efficient. Even though it is very difficult to convert an energy supply entirely to its intended purpose, converting electricity to hot water in a water heater comes very close. That’s because heat, the waste product that usually makes an energy conversion system less efficient, is actually the intended product of the conversion. If the conversion from electricity to heat occurs inside the tank of water, which is usually the case with electric hot water heaters, very little energy is lost, and we can say the efficiency is 99 percent. By contrast, a typical natural gas water heater, which transfers energy to water with a flame below the tank and vents waste heat and by-products of combustion to the outside, has an efficiency of about 80 percent. The overall efficiency, however, is actually lower because we have not factored in the energy expended to extract, process, and deliver natural gas to the home. But if a coal-fired power plant is the source of the electricity that fuels the electric water heater, we have to take into account the fact that conversion of fossil fuel into electricity is only about 35 percent efficient. This means that, even though an electric water heater has a higher direct efficiency than a natural gas water heater, the overall efficiency of the electric water heating system is lower—35 percent for the electric water heater versus something less than 80 percent—but not much less—for the gas water heater. There may be many situations in which it is a better choice to heat water with electricity rather than natural gas. But from an environmental perspective, it is important to look at the overall system efficiency when considering the pros and cons of an energy choice.

EFFICIENCY AND TRANSPORTATION

Because nearly 30 percent of energy use in the United States is for transportation, this is an area in which efficiency is particularly important. Transportation—the movement of people and goods—is achieved primarily through the use of vehicles fueled by petroleum products, such as gasoline and diesel, and by electricity. These vehicles contribute to air pollution and greenhouse gas emissions. However, some modes of transportation are more efficient than others. As you might expect, traveling by train or bus—that is, by public transportation—is much more efficient than traveling by car, especially when there is only one person in the car. And public ground transportation is usually more efficient than air travel. TABLE 12.1 shows the efficiencies of different modes of transportation. Note that the energy values report only energy consumed, in megajoules (MJ, \(10^6\) J), per passenger-kilometer traveled and do not include the embodied energy used to build the different vehicles. Train and motorcycle are the most energy-efficient modes of
transportation shown. If a car contained four passengers, we would divide the value in **TABLE 12.1** for a lone driver by four, and thus the car would be the most efficient means of transportation. Cars traveling with four riders are relatively rare in the United States, however; single-occupant vehicles are the most common means of transportation. Do the Math “Efficiency of Travel” shows you how to calculate the efficiencies of different modes of transportation.

<table>
<thead>
<tr>
<th>Mode</th>
<th>MJ per passenger-kilometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>2.1</td>
</tr>
<tr>
<td>Passenger car (driver alone)</td>
<td>3.6</td>
</tr>
<tr>
<td>Motorcycle</td>
<td>1.1</td>
</tr>
<tr>
<td>Train (Amtrak)</td>
<td>1.1</td>
</tr>
<tr>
<td>Bus</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**TABLE 12.1** Energy expended for different modes of transportation in the United States

Source: All data are from Bureau of Transportation Statistics, U.S. Department of Transportation, except for the passenger car, which was determined by assuming one occupant per vehicle obtaining average fuel efficiency of 22 mpg (9.4 km per liter).

Transportation efficiency calculations do not take into account convenience, comfort, or style. Many people in the developed world are quite particular about how they get from place to place and want the independence of a personal vehicle. They also tend to have strong feelings about what type of personal vehicle is most desirable. In the United States, light trucks—a category that usually includes sportutility vehicles (SUVs), minivans, and pickup trucks—account for roughly one-half of total automobile sales, while hybrid electric vehicles account for between 2 and 3 percent of total sales.

**DO THE MATH**

**Efficiency of Travel**

Imagine that you had unlimited time and you needed to get from Washington, D.C., to Cleveland, Ohio. The distance is roughly 600 km (370 miles). For each mode of transportation, calculate how many megajoules of energy you would use.

Using the data in **TABLE 12.1**, we can determine the following:

- **Air**: 2.1 MJ/passenger-kilometer × 600 km/trip = 1,260 MJ/passenger-trip
- **Car**: 3.6 MJ/passenger-kilometer × 600 km/trip = 2,160 MJ/passenger-trip
- **Train**: 1.1 MJ/passenger-kilometer × 600 km/trip = 660 MJ/passenger-trip
Bus  \[1.7 \text{ MJ/pasenger-kilometer} \times 600 \text{ km/trip} \]
\[= 1,020 \text{ MJ/pasenger-trip}\]

If a gallon of gasoline contains 120 MJ, how many gallons of gasoline does it take to make the trip by car?

\[
\frac{2,160 \text{ MJ/pasenger-trip}}{120 \text{ MJ/gallon}} = 18 \text{ gallons/pasenger-trip}
\]

Examining total joules expended makes it clear that the train is the most energy-efficient means of travel. Driving alone in a car is the least energy-efficient.

**Your Turn:** If you could carpool with three other people who needed to make the same trip, what would the energy expenditure be for each person?

Light trucks are comparatively heavy vehicles and so generally have mileage ratings of less than 8.5 km per liter, or 20 miles per gallon (mpg). Because they are exempt from certain vehicle emission standards, they emit more of certain air pollutants per liter of fuel combusted than passenger cars. Smaller cars with standard internal combustion engines can travel up to 19 km per liter (45 mpg) on the highway. Hybrid passenger cars, which use a gasoline engine, electric motors, and regenerative braking (a system that reclaims energy normally dissipated when car brakes are applied), obtain closer to 21 km per liter (50 mpg). Electric cars and plug-in hybrid electric cars, which are becoming more common in the United States, obtain even better fuel efficiency.

Despite the availability of fuel-efficient vehicles, many people drive vehicles that yield relatively low fuel efficiencies. As **FIGURE 12.6** shows, the overall fuel efficiency of the U.S. personal vehicle fleet declined from 1985 through 2005 as people chose light trucks and SUVs over cars. Only in the last few years have vehicle choice changed and vehicle efficiency slowly increased. Recently, legislation was passed to increase the average fuel efficiency of new cars and light trucks sold each year so as to deliver a combined fleet average of 15 km per liter (35 mpg) by 2016.
Figure 12.6 Overall fuel efficiency of U.S. automobiles. As more buyers moved from cars to light trucks (a category that includes pickup trucks, minivans, and SUVs) for their personal vehicles, the fuel economy of the total U.S. fleet declined. Only recently has it begun to increase. [After U.S. Environmental Protection Agency.]

Energy efficiency is an important consideration when making fuel and technology choices, but it is not the only factor we must consider. Determining the best fuel for the job is not always easy, and it involves trade-offs among convenience, ease of use, safety, cost, and pollution.

12.2 Electricity is a convenient form of energy

Because it can be generated from many different sources, from fossil fuels to the Sun, electricity is a form of energy in its own category. Coal, oil, and natural gas are primary sources of energy. Electricity is a secondary source of energy, meaning that we obtain it from the conversion of a primary source. By the nature of being a secondary source, electricity is an energy carrier: something that can move and deliver energy in a convenient, usable form to end users.

Approximately 40 percent of the energy used in the United States is used to generate electricity. But because of conversion losses during the electricity generation process, of that 40 percent, only 13 percent is available for end uses. In this section we will look at some of the basic concepts and issues related to generating electricity from fossil fuels. Chapter 13 discusses electricity generation from renewable energy sources.

12.2. Electricity Generation
Electricity is produced by conversion of primary sources of energy such as coal, natural gas, or wind. Electricity is clean at the point of use; no pollutants are emitted in your home when you use a light bulb or computer. When electricity is produced by burning fossil fuels, however, pollutants are released at the location of its production. In addition, as we have seen, the transfer of energy from a fuel to electricity is only about 35 percent efficient. Therefore, although electricity is highly convenient, from the standpoint of efficiency of the overall system and the total amount of pollution released, it is more desirable to transfer heat directly to a home with wood or oil combustion, for example, than via electricity generated from the same materials. The energy source that entails the fewest conversions from its original form to the end use is likely to be the most efficient.

Many types of fossil fuels, as well as nuclear fuels, can be used to generate electricity. Regardless of which fuel is used, all thermal power plants work in the same basic way: they convert the potential energy of a fuel into electricity. FIGURE 12.7 illustrates the major features of a typical coal-burning power plant. Fuel—in this case, coal—is delivered to a boiler, where it is burned. The burning fuel transfers energy to water, which becomes steam. The kinetic energy contained within the steam is transferred to the blades of a turbine, a large device that resembles a fan or a jet engine. As the energy in the steam turns the turbine, the shaft in the center of the turbine turns the generator, which generates electricity. The electricity that is generated is then transported along a network of interconnected transmission lines known as the electrical grid, which connects power plants together and links them with end users of electricity. Once the electricity is on the grid, it is distributed to homes, businesses, factories, and other electricity consumers, where it may be converted into heat energy for cooking, kinetic energy in motors, or radiant energy in lights, or used to operate electronic and electrical devices. After the steam passes through the turbine, it is condensed back into water. Sometimes the water is cooled in a cooling tower or discharged into a nearby body of water. As we saw in Chapter 9, once-through use of water for thermal electricity generation is responsible for about one-half the water consumption in the United States.
Figure 12.7  A coal-fired electricity generation plant. Energy from coal combustion converts water into steam, which turns a turbine. The turbine turns a generator, which produces electricity.

EFFICIENCY OF ELECTRICITY GENERATION  Whereas a typical coal-burning power plant has an efficiency of about 35 percent, newer coal-burning power plants may have slightly higher efficiencies. Power plants using other fossil fuels can be even more efficient. An improvement in gas combustion technology has led to the combined cycle natural gas–fired power plant, which has two turbines and generators. Natural gas is combusted, and the combustion products turn a gas turbine. In addition, the waste heat from this process boils water, which turns a conventional steam turbine. For this reason, a combined cycle plant can achieve efficiencies of up to 60 percent.  A typical power plant in the United States might have a capacity—that is, a maximum electrical output—of 500 megawatts (MW). This means that when the plant is operating, it generates 500 MW of electricity. If the plant operated for one day, it would generate 500 MW × 24 hours = 12,000 megawatt-hours (abbreviated MWh). Most home electricity is measured in kilowatt-hours (abbreviated kWh). So the typical power plant we’ve just described would generate 12,000,000 kWh in a day. If it operated for 365 days per year, it would generate 365 times that daily amount.
Most power plants, however, do not operate every day of the year. They must be shut down for some time to allow for maintenance, refueling, or repairs. Therefore, it is useful to measure the amount of time a plant actually operates in a year. This number—the fraction of the time a plant is operating—is known as its **capacity factor**. Most thermal power plants have capacity factors of 0.9 or greater. As we will see in Chapter 13, power plants using some forms of renewable energy, such as wind, may have a capacity factor of only about 0.25. Do the Math “Calculating Electricity Supply” shows you how to calculate the amount of energy a power plant can supply.

When it is time to start up a power plant, nuclear and coal-fired plants may take a number of hours, or even a full day, to come up to full generating capacity. Because of the time it takes for them to become operational, electric companies tend to keep nuclear and coal-fired plants running at all times. As demand for electricity changes during the day or week, plants that are more easily powered up, such as those that use natural gas, oil, water, or wood, are used.

**Figure 12.8** Fuels used for electricity generation in the United States. Coal is the fuel most commonly used for electricity generation. [Data from U.S. Department of Energy, Energy Information Administration, 2009.]

**COGENERATION** The use of a fuel to generate electricity and produce heat is known as **cogeneration**. Also called combined heat and power, cogeneration is a method employed by certain users of steam for obtaining greater efficiencies. If steam used for industrial purposes or to heat buildings is diverted to turn a turbine first, the user will achieve greater overall efficiency than by generating heat and electricity separately. Cogeneration efficiencies can be as high as 90 percent, whereas steam
heating alone might be 75 percent efficient, and electricity generation alone might be 35 percent efficient.

There are over 17,000 power plants in the United States. In 2009, they generated 3.9 billion MWh. **FIGURE 12.8** shows the fuels that were used to generate this electricity. As we can see, coal-fired power plants are the backbone of electricity generation in the United States, responsible for 45 percent of all electricity produced. Natural gas, at 23 percent, and nuclear energy, at 20 percent, account for most of the remainder of our generating capacity. Together, these three sources, plus a very small amount of oil, account for 89 percent of electricity generation in the United States. Water and other renewable energy resources such as wind and solar energy account for the remainder of the electricity generated in the country.

**DO THE MATH**

**Calculating Electricity Supply**

According to the U.S. Department of Energy, a typical home in the United States uses approximately 900 kWh of electricity per month. On an annual basis, this is

900 kWh/month × 12 months/year = 10,800 kWh/year

How many homes can a 500 MW power plant with a 0.9 capacity factor support?

Begin by determining how much electricity the plant can provide per month:

500 MW × 24 hours/day × 30 days/month × 0.9 = 324,000 MWh/month

1 MWh equals 1,000 kWh, so to convert MWh per month to kWh per month, we multiply by 1,000:

324,000 MWh/month × 1,000 kWh/MWh = 324,000,000 kWh/month

So

\[
\frac{324,000,000 \text{ kWh/month}}{900 \text{ kWh/month/home}} = 360,000 \text{ homes}
\]

On average, a 500 MW power plant can supply roughly 360,000 homes with electricity.

**CHECKPOINT**

- What is the basic process by which the energy in a fuel is converted into electricity?
- What are the major fuels that are used to generate electricity in the United States?
- What is a combined cycle plant, and what is cogeneration?

- **12.3** Fossil fuels provide most of the world’s energy

Fossil fuels provide most of the energy used in both developed and developing countries. The vast majority of the fossil fuels we use—coal, oil, and natural gas—come from deposits of organic matter that were formed 50 million to 350 million years
ago. When organisms die, decomposers break down most of the dead biomass aerobically, and it quickly reenters the food web, as we saw in Chapter 3. However, in places such as swamps, river deltas, and the ocean floor, a large amount of detritus may build up quickly in an anaerobic environment. Under these conditions, decomposers cannot break down all of the detritus. As this material is buried under succeeding layers of sediment and exposed to heat and pressure, the organic compounds within it are chemically transformed into high-energy solid, liquid, and gaseous components that are easily combusted. Because they come from ancient biomass, these components—coal, oil, and natural gas—are called fossil fuels. **FIGURE 3.11**, which shows the contemporary carbon cycle, illustrates the process of fossil fuel formation.

12.3. Coal

We have seen that coal is the fuel most commonly used for electricity generation in the United States. In Chapter 8 we learned about the various methods of extracting coal from the ground. But how exactly is coal formed? **Coal** is a solid fuel formed primarily from the remains of trees, ferns, and other plant materials that were preserved 280 million to 360 million years ago. There are four types of coal: ranked from lesser to greater age, exposure to pressure, and energy content, they are lignite, subbituminous, bituminous, and anthracite. A precursor to coal, called peat, is made up of partly decomposed organic material, including mosses. **FIGURE 12.9** shows how the different types of coal are formed. Starting with an organic material such as peat, increasing time and pressure produce successively denser coal with more carbon molecules, and more potential energy, per kilogram.
The largest coal reserves are found in the United States, Russia, China, and India. The countries that are currently producing the greatest amounts of coal are China, the United States, India, and Australia.

**ADVANTAGES AND DISADVANTAGES OF COAL**

Because it is energy-dense and plentiful, coal is used to generate electricity and for industrial processes such as making steel. In many parts of the world, coal reserves are relatively easy to exploit by surface mining. The technological demands of surface mining are relatively small, and the economic costs are low. As surface coal is used up and becomes harder to find, however, subsurface mining becomes necessary. With subsurface mining, the technological demands and costs increase, and the human health consequences increase as well, as we saw in Chapter 8. Once it is extracted from the ground, coal is relatively easy to handle and needs little refining before it is burned. It can be transported to power plants and factories by train, barge, or truck. All of these factors make coal a relatively easy fuel for any country to use, regardless of its technological development and infrastructure.

Although coal is a relatively inexpensive fossil fuel, its use does have several disadvantages. Coal contains a number of impurities, including sulfur, that are released into the atmosphere when it is burned. The sulfur content of coal typically ranges from 0.4 to 4 percent by weight. Lignite and anthracite have a relatively low sulfur content, whereas bituminous coal often has a much higher sulfur content. Trace metals such as mercury, lead, and arsenic are also found in coal. Combustion of coal results in the release of these impurities, which leads to an increase of sulfur dioxide and other air pollutants, such as particulates, in the atmosphere, as we will see in Chapter 15. Compounds that are not released into the atmosphere remain behind in the resulting ash.

According to the U.S. Department of Energy, there are 1,450 coal mines in the United States, and they produced more than 1 billion metric tons of coal in 2008. Most of that coal is burned in the United States, and anywhere from 3 to 20 percent of it remains behind as ash. As a result, large deposits of ash are often stored near coal-burning power plants. One such ash deposit—a mixture of ash and water—was kept in a holding pond at a power plant near Knoxville, Tennessee. In December 2008, the retaining wall that contained the ash gave way and spilled 4.1 billion liters (1.1 billion gallons) of ash(Figure 12.10). Three houses were destroyed by the flow of muddy ash, which covered over 121 hectares (300 acres) of land. The event was the largest of its kind in U.S. history, and the cleanup is still ongoing.
Coal is 60 to 80 percent carbon. When it is burned, most of that carbon is converted into CO$_2$, and energy is released in the process. When it is combusted, coal produces far more CO$_2$ per unit energy released than either oil or natural gas. This CO$_2$ contributes to the increasing atmospheric concentrations of CO$_2$ discussed in Chapter 1, Chapter 3, and Chapter 19.

12.3. Petroleum

Petroleum, another widely used fossil fuel, is a fluid mixture of hydrocarbons, water, and sulfur that occurs in underground deposits. While coal is an ideal fuel for stationary combustion applications, such as power plants and industry, the fluid nature of petroleum products such as oil and gasoline makes them ideal for mobile combustion applications, such as vehicles.
Figure 12.11 Petroleum accumulation underground. Petroleum migrates to the highest point in a formation of porous rock and accumulates there. Such accumulations of petroleum can be removed by drilling a well.

Petroleum is formed from the remains of ocean-dwelling phytoplankton (microscopic algae) that died 50 million to 150 million years ago. Deposits of phytoplankton are found in locations where porous sedimentary rocks, such as sandstone, are capped by nonporous rocks. Petroleum forms over millions of years and fills the pore spaces in the rock. Geologic events related to the tectonic cycle we discussed in Chapter 8 may deform the rock layers so that they form a dome. The petroleum is less dense than the rock, so over time, it migrates upward toward the highest point in the porous rock, where it is trapped by the nonporous rock, as Figure 12.11 shows. In certain locations, petroleum flows out under pressure the way water flows from an artesian well, as described in Chapter 9. But usually petroleum producers must drill wells into a deposit and extract the petroleum with pumps. After extraction, the petroleum must be transported by pipeline, if the well is on land, or by supertanker, if it is underwater, to a petroleum refinery.

Petroleum contains natural gas. As we can see from Figure 12.11, some of the gas separates out naturally. That’s why you sometimes see a burning flame, known as a gas flare, in photographs of oil wells. The oil workers are flaring, or burning off, the natural gas under controlled conditions to prevent an explosion. Some of the gas is also extracted for use as fuel, as we will see in the following section.

Liquid petroleum that is removed from the ground is known as crude oil. The U.S. Department of Energy refers to oil, crude oil, and petroleum more or less as equivalent substances, and we will do the same in this chapter. Crude oil can be further refined into a variety of compounds. These compounds, including tar and asphalt, gasoline, diesel, and kerosene, are distinguished by the temperature at which
they boil and can therefore be separated by heating the petroleum. This process takes place in an oil refinery, a large factory of the kind shown in this chapter’s opening photograph. The refining process is complex and dangerous and requires a major financial investment. There are roughly 150 oil refineries in the United States; some of the larger ones can refine over 80 million liters (21 million gallons) per day. Oil production and sales are measured in barrels of oil; one barrel equals 160 liters (42 gallons).

As we saw in **FIGURE 12.4**, the United States uses more petroleum than any other fuel—roughly 3.1 billion liters (816 million gallons) of petroleum products *per day*. Gasoline accounts for roughly one-half of that amount. The primary use of petroleum products is for transportation. Petroleum is also the raw material for petrochemicals, such as plastics, lubricants, raw materials for pharmaceuticals, and cleaning solvents. Worldwide petroleum consumption is almost 14 billion liters (3.7 billion gallons) per day. Thus the United States is responsible for about 22 percent of worldwide petroleum consumption.

The top petroleum-producing countries are Saudi Arabia, Russia, the United States, Iran, China, Canada, and Mexico, in that order. These seven countries account for roughly one-half of worldwide oil production.

**ADVANTAGES AND DISADVANTAGES OF PETROLEUM** Because petroleum is a liquid, it is extremely convenient to transport and use. It is relatively energy-dense and is cleaner-burning than coal. For these reasons, it is an ideal fuel for mobile combustion engines such as those found in automobiles, trucks, and airplanes. But because it is a fossil fuel, it releases CO$_2$ when burned. However, for every joule of energy released, oil produces only about 85 percent as much CO$_2$ as coal.

Oil, like coal, contains sulfur and trace metals such as mercury, lead, and arsenic, which are released into the atmosphere when it is burned. Some sulfur can be removed during the refining process, so it is possible, though more expensive, to obtain low-sulfur oil.

As we have seen, oil must be extracted from under the ground or beneath the ocean. Whenever oil is extracted and transported, there is the potential for oil to leak from the wellhead or be spilled from a pipeline or tanker. Some oil naturally escapes from the rock in which it was stored and seeps into water or out onto land. However, commercial oil extraction has greatly increased the number of leakage and spillage events and the amount of oil loss to land and water around the world. As we saw in this chapter’s opening story, the largest oil spill in the United States until 2010 was the *Exxon Valdez* oil tanker accident in 1989. More recently, the blowout of the BP Deepwater Horizon oil well, drilled 81 km (50 miles) off the coast of Louisiana in
1,524 m (5,000 feet) of water, has led to a spill of well over 780 million liters (206 million gallons) of oil (FIGURE 12.12).

![Aerial view of an oil spill.](image)

Larger oil spills have occurred elsewhere in the world. For example, during the 1991 Persian Gulf War, approximately 912 million liters (240 million gallons) of petroleum were spilled when wellheads were deliberately sabotaged or destroyed by the Iraqi army in Kuwait.

It is important to consider the various ways in which oil is spilled into the natural environment. A 2003 National Academy of Sciences study found that oil extraction and transportation were responsible for a relatively small fraction of the oil spilled into marine waters worldwide. Roughly 85 percent of the oil entering marine waterways came from runoff from land and rivers, airplanes, and small boats and personal watercraft, including deliberate and accidental releases of waste oil.

In the United States, debates continue over the trade-off between extracting oil domestically and the consequences for habitat and species living near oil wells or pipelines. For example, when a 1,300 km (800-mile) pipeline was constructed to transport oil overland from the North Slope of Alaska to tankers that would carry it to the continental United States, wildlife biologists predicted that the pipeline might melt permafrost and interfere with the calving grounds of caribou. Scientists continue to monitor the pipeline, but so far have come to no conclusions about its environmental impact. The debate about the environmental effects of land-based oil extraction has continued with the proposal to allow oil exploration in the Arctic National Wildlife
Refuge (ANWR), a 7.7 million hectare (19 million acre) tract of land in northeastern Alaska (FIGURE 12.13). Proponents of exploration suggest that ANWR might yield 95 billion liters (25 billion gallons) to 1.4 trillion liters (378 billion gallons) of oil and substantial quantities of natural gas. Opponents maintain that opening ANWR to exploration and petroleum extraction will harm pristine habitat for many species and affect people in the area as well.
Humans, as well as wildlife, have been harmed by oil extraction. In Nigeria and many other developing countries, oil fields are adjacent to villages. Thick, gelatinous crude oil covers the ground where people walk, sometimes in bare feet, and oil flaring—the burning off of excess natural gas—takes place close to homes. Concerns about the effects of oil extraction on health, human rights, and environmental justice have led to violent political protests against oil companies in Nigeria and elsewhere.

### 12.3. Natural Gas

We have already mentioned natural gas in connection with petroleum, since it exists as a component of petroleum in the ground as well as in gaseous deposits separate from petroleum. Natural gas is 80 to 95 percent methane (CH$_4$) and 5 to 20 percent ethane, propane, and butane. Because natural gas is lighter than oil, it lies above oil in petroleum deposits (see **Figure 12.11**). Natural gas is generally extracted in association with petroleum; only recently has exploration specifically for natural gas been conducted.

The two largest uses of natural gas in the United States are electricity generation and industrial processes. Natural gas is also used to manufacture nitrogen fertilizer and in residences as an efficient fuel for cooking, heating, and operating clothes dryers and water heaters. Compressed natural gas can be used as a fuel for vehicles, but because it must be transported by pipeline, it is not accessible in all parts of the United States and is therefore unlikely to become an important fuel for cars. Liquefied petroleum gas (LPG)—which is similar to natural gas, but in a liquid form—is a slightly less energy-dense substitute. LPG can be transported via train or truck and stored at the point of use in tanks. This fuel is available practically everywhere in the United States and is used in place of natural gas and for portable barbecue grills and heaters. Overall, natural gas and LPG supply 24 percent of the energy used in the United States.

### ADVANTAGES AND DISADVANTAGES OF NATURAL GAS

Because of the extensive natural gas pipeline system in many parts of the United States, roughly one-half of homes use natural gas for heating. Compared with coal and oil, natural gas contains fewer impurities and therefore emits almost no sulfur dioxide or particulates during combustion. And for every joule of energy released during combustion, natural gas emits only 60 percent as much CO$_2$ as coal. On the other hand, unburned natural gas—methane—that escapes into the atmosphere is itself a potent greenhouse gas that is 25 times more efficient at absorbing infrared energy than CO$_2$. The leaking of natural gas
after extraction is a suspected contributor to the steep rise in atmospheric methane concentrations that was observed in the 1990s.

While natural gas is referred to as the “clean” fossil fuel, its extraction and use still lead to environmental problems (FIGURE 12.14). The process of exploring for natural gas involves the “thumper trucks” mentioned in this chapter’s opening story. The process of drilling and opening up the rock containing the natural gas, called host rock, in order to release natural gas is called hydraulic fracturing, or “fracking.” This process entails drilling with water, sand, and proprietary chemicals whose names and effects do not have to be released to the public by the companies that use them. Large quantities of water are used during hydraulic fracturing; this water becomes contaminated with chemicals during the process and must be disposed of afterward. There is often groundwater contamination resulting from the drilling of natural gas wells.

12.3. Other Fossil Fuels: Oil Sands and Liquefied Coal

There are other types of fossil fuel deposits that contain a great deal of energy, but are not readily available. When we consider using these energy resources, the energy return on energy investment is always an important consideration. Not all petroleum is easily extractable in conventional oil wells. Oil sands are slow-flowing, viscous deposits of bitumen mixed with sand, water, and clay. Bitumen, often called tar or pitch, is a degraded type of petroleum that forms when a petroleum deposit is not capped with nonporous rock. The petroleum migrates close to the
surface, where bacteria metabolize some of the light hydrocarbons while others evaporate. The remaining mix no longer flows at ambient temperatures and pressures. It can be extracted by surface mining. Although oil sand exploitation promises to extend our petroleum supply, it could have serious negative environmental impacts. The mining of bitumen is much more energy-intensive than conventional drilling for crude oil. As we saw in Chapter 8, surface mining creates large open pits. Extraction of the bitumen from the other material contaminates roughly 2 to 3 L of water for every liter of bitumen obtained, and many oil sands are located in areas where water is not an abundant resource. In addition, because oil sands require so much energy to process before they even get to a refinery, the overall system efficiency is lower, and the resulting CO₂ release greater, than for conventional oil production. Whereas the availability of petroleum may become much more limited in this century as supplies diminish, the United States and China both have immense coal reserves. The technology to convert solid coal into a liquid fuel—a process known as CTL, short for “coal-to-liquid”—has been available for decades. CTL was widely used by the German military during World War II and has been used by other countries since then. But producing liquefied coal is relatively expensive and has many of the same drawbacks as exploiting oil sands. In terms of total energy content, there is over 1,000 times more energy in the world’s coal reserves than in the world’s petroleum reserves. Because there is so much coal in the United States, CTL has the potential to eliminate U.S. dependence on foreign oil. On the other hand, the U.S. Environmental Protection Agency estimates that total greenhouse gas emissions from liquefied coal are more than twice those from conventionally produced oil, and as we have seen, the environmental impacts of coal mining can be severe.

**CHECKPOINT**

- How are the different types of coal formed?
- How is oil formed, and why does it need to be refined?
- What are the major advantages and disadvantages of using coal, oil, and natural gas?

### 12.4 Fossil fuels are a finite resource

Although we know that the supply of fossil fuels is finite, there is some discussion within the environmental science community on whether or not that matters. Recall our discussion in Chapter 7 about the creativity of the human population. Many people believe that we will apply that creativity to the development of new energy sources. In
the meantime, total energy use continues to increase, even though energy use per person has leveled off and energy use per unit of gross domestic product (GDP), known as **energy intensity**, has been steadily decreasing, as *FIGURE 12.15* shows. In other words, we are using energy more efficiently in order to do what we need to do, but because there are more of us and we are doing more things that use energy, our overall energy use has increased. For example, think about how many electronic devices you have, then ask your parents or grandparents how many electronic devices they had at your age.

*FIGURE 12.15* U.S. energy use per capita and energy intensity. Our energy use per capita has been level while our energy intensity, or energy use per dollar of GDP, has been decreasing in recent years. However, because of our increasing population, our overall energy use continues to increase. [Data from U.S. Department of Energy, Energy Information Administration, 2009.]

Because fossil fuels take millions of years to form, they are nonrenewable resources. By definition, then, the use of fossil fuels is not sustainable because there is no way to limit our consumption to the rate at which they are being formed. Experts debate whether our economy will at some point be limited by the availability of this energy resource. In recent years, concerns have shifted away from the supply of fossil fuels to the consequences of fossil fuel combustion, particularly the release of CO\(_2\) and its contribution to global warming. Many environmental scientists believe that these
consequences will manifest themselves in adverse ways long before we run out of fossil fuels.

12.4. The Hubbert Curve

In 1969, M. King Hubbert, a geophysicist and oil company employee, published a graph showing a bell-shaped curve representing oil use (FIGURE 12.16). The graph, which became known as the Hubbert curve, projected the point at which world oil production would reach a maximum and the point at which we would run out of oil. Hubbert used two estimates of total world petroleum reserves: an upper estimate and a lower estimate. He found that the total reserves did not greatly influence the time it would take to use up all of the oil in known reserves. Rather, he predicted that oil extraction and use would increase steadily until roughly half the supply had been used up. At that point, known as peak oil, extraction and use would begin to decline. Some oil experts believe we have already reached peak oil, while others maintain that we may reach it very soon. Back in 1969, Hubbert predicted that 80 percent of the world’s total oil supply would be used up in roughly 60 years.

![Figure 12.16 A generalized version of the Hubbert curve.](image)

Whether an upper estimate or a lower estimate of total petroleum reserves is used, the date by which petroleum reserves will be depleted does not change substantially. [After M. K. Hubbert, The energy resources of the Earth, in Energy and Power, A Scientific American Book (W. H. Freeman, 1971].]

Although there have been discoveries of large oil fields since Hubbert did his work, the conclusion he drew from his model still holds. Regardless of the exact amount of the total reserves, the total number of years we use petroleum will fall within a relatively narrow time window. That is, when we identify a fuel source, we tend to use it until we come upon a better fuel source. As a number of energy experts are fond of saying, “We did not move on from the Stone Age because we ran out of stones.” Similarly, many
people believe that ingenuity and technological advances in the renewable energy sector will one day render oil much less desirable.

12.4. The Future of Fossil Fuel Use

If current global use patterns continue, we will run out of conventional oil supplies in less than 40 years. Natural gas supplies will last slightly longer. Coal supplies will last for at least 200 years, and probably much longer. While these predictions assume that we will continue our current use patterns, advances in technology, a shift to nonfossil fuels, or changes in social choices and population patterns could alter them.

In recent years, with greater acceptance of the theory that global climate change is resulting from anthropogenic increases in atmospheric greenhouse gas concentrations, a large number of researchers have suggested that the question we should be asking is not “When will we run out of oil?” but rather, “How can we transition away from fossil fuels before their use causes further problems?”

Concerns about the scarcity, environmental impacts—especially the influence of CO₂ on global climate change—and rising costs of fossil fuels present many opportunities. Rising oil prices create a powerful incentive to invest in alternative energy resources and conservation. As we will see in Chapter 13, people have begun to explore the possibility of a new infrastructure to deliver wind energy, hydroelectricity, and solar energy in novel ways. On the other hand, the higher price of oil makes formerly unproductive mining and extraction methods cost-competitive, and so may result in greater total production of fossil fuels.

There is one other conventional, nonrenewable fuel that offers a very attractive feature: it does not contribute significantly to the addition of greenhouse gases to the atmosphere. That fuel is uranium.

CHECKPOINT

- Explain the relationship between energy intensity and energy use per capita.
- Describe the Hubbert curve and its significance.
- What are the major considerations involved in the future of fossil fuels?
will continue our current use patterns, advances in technology, a shift to nonfossil fuels, or changes in social choices and population patterns could alter them. In recent years, with greater acceptance of the theory that global climate change is resulting from anthropogenic increases in atmospheric greenhouse gas concentrations, a large number of researchers have suggested that the question we should be asking is not “When will we run out of oil?” but rather, “How can we transition away from fossil fuels before their use causes further problems?” Concerns about the scarcity, environmental impacts—especially the influence of CO$_2$ on global climate change—and rising costs of fossil fuels present many opportunities. Rising oil prices create a powerful incentive to invest in alternative energy resources and conservation. As we will see in Chapter 13, people have begun to explore the possibility of a new infrastructure to deliver wind energy, hydroelectricity, and solar energy in novel ways. On the other hand, the higher price of oil makes formerly unproductive mining and extraction methods cost-competitive, and so may result in greater total production of fossil fuels. There is one other conventional, nonrenewable fuel that offers a very attractive feature: it does not contribute significantly to the addition of greenhouse gases to the atmosphere. That fuel is uranium.

**CHECKPOINT**

- Explain the relationship between energy intensity and energy use per capita.
- Describe the Hubbert curve and its significance.
- What are the major considerations involved in the future of fossil fuels?
  - **12.5 Nuclear energy is getting a second look**

Because the combustion of fossil fuels releases large quantities of CO$_2$ into the atmosphere, people have considered the advantages and disadvantages of many other energy sources. One of these alternatives, nuclear energy, has often been rejected because of concerns about the dangers of nuclear accidents, radioactivity, and the proliferation of radioactive fuels that could be used in weapons. Recently, however, nuclear energy has received positive attention, even from self-proclaimed environmentalists, because of its relatively low emissions of CO$_2$.

**12.5. The Use of Fission in Nuclear Reactors**
Figure 12.17  Nuclear fission. Energy is released when a neutron strikes a large atomic nucleus, which then splits into two or more parts.

Electricity generation from nuclear energy uses the same basic process as electricity generation from fossil fuels: steam turns a turbine that turns a generator that generates electricity. The difference is that a nuclear power plant uses a radioactive isotope, uranium-235 (\(^{235}\text{U}\)), as its fuel source. We presented the concepts of isotopes, radioactive decay, and half-lives in Chapter 2. Radioactive decay occurs when a parent radioactive isotope emits alpha or beta particles or gamma rays. Here, we need to introduce one more concept before being able to fully describe a nuclear power plant. The naturally occurring isotope \(^{235}\text{U}\), as well as other radioactive isotopes, undergoes a process called fission.

Fission, shown in FIGURE 12.17, is a nuclear reaction in which a neutron strikes a relatively large atomic nucleus, which then splits into two or more parts. This process releases additional neutrons and energy in the form of heat. The additional neutrons can, in turn, promote additional fission reactions, which leads to a chain reaction of nuclear fission that gives off an immense amount of heat energy. In a nuclear power plant, that heat energy is used to produce steam, just as in any other thermal power plant. However, 1 g of \(^{235}\text{U}\) contains 2 million to 3 million times the energy of 1 g of coal.
Uranium-235 is one of the more easily fissionable isotopes, which makes it ideal for use in a nuclear reactor. A neutron colliding with $^{235}\text{U}$ splits the uranium atom into smaller atoms, such as barium and krypton, and three neutrons. The reaction is as follows:

$$1 \text{ neutron} + ^{235}\text{U} \rightarrow ^{142}\text{Ba} + ^{91}\text{Kr} + 3 \text{ neutrons in motion (kinetic energy)}$$

Many other radioactive daughter products are released as well. A properly designed nuclear reactor will harness the kinetic energy from the three neutrons in motion to produce a self-sustaining chain reaction of nuclear fission. The by-products of the nuclear reaction include radioactive waste that remains hazardous for many half-lives—that is, hundreds of thousands of years or longer.

**FIGURE 12.18** shows how a nuclear reactor works. The containment structure encloses the nuclear fuel—which is contained within cylindrical tubes called **fuel rods**—and the steam generator. Uranium fuel is processed into pellets, which are then put into the fuel rods. A typical nuclear reactor might contain hundreds of bundles of fuel rods in the center, or reactor core, within the containment structure.
Within the containment structure, heat from nuclear fission is used to heat water, which circulates in a loop. This loop passes close to another loop of water, and heat is transferred from one loop to the other. In the process, steam is produced, which turns a turbine, which turns a generator, just as in most other thermal power plants. The nuclear power plant shown in Figure 12.18 is a light-water reactor, the only type of reactor used in the United States and the most common type used elsewhere in the world.

The objective of a nuclear power plant is to harness the heat energy from fission to make steam. But the plant must be able to slow the fission reaction to allow collisions to take place at the appropriate speed. To do this, nuclear reactors contain a moderator, such as water, to slow down the neutrons so that they can effectively trigger the next chain reaction. There is also a risk that the reaction will run out of control. Nuclear reactors contain control rods, cylindrical devices that can be inserted between the fuel rods to absorb excess neutrons, thus slowing or stopping the fission reaction. This is done routinely during the operation of the plant because nuclear fuel rods left uncontrolled will quickly become too hot and melt—an event called meltdown—or cause a fire, either of which could lead to a catastrophic nuclear accident. Control rods are also inserted when the plant is being shut down during an emergency or for maintenance and repairs.

Depending on the ore, it may take up to 900 kg (2,000 pounds) of uranium ore to produce 3 kg (6.6 pounds) of nuclear fuel. In order to obtain uranium, miners remove large amounts of the host rock, extract and concentrate the uranium, and leave the remaining material in slag piles. Australia, the western United States, and parts of Canada have large commercial uranium mining operations for nuclear fuel. As we saw in Chapter 8, the mining of any material requires fossil fuel energy and results in mine tailings. This is also true for uranium, although, as we have noted, a much smaller volume and mass of uranium is needed to generate a quantity of electricity than coal.

Nuclear power plants rely on $^{235}\text{U}$ as their fuel. However, most uranium ores contain as much as 99 percent $^{238}\text{U}$, another isotope of uranium that occurs with $^{235}\text{U}$ but does not fission as easily. Therefore, when uranium ore is mined, it must be chemically enriched—a process to increase its concentration—in $^{235}\text{U}$ to be useful as a fuel. Typically, suitable nuclear fuel contains 3 percent or greater $^{235}\text{U}$.

12.5. **Advantages and Disadvantages of Nuclear Energy**
Nuclear power plants do not produce air pollution during their operation, so proponents of nuclear energy consider it “clean” energy. In countries with limited fossil fuel resources, nuclear energy is one way to achieve independence from imported oil. Nuclear energy generates 70 percent of electricity in France, and it is widely used in Lithuania, Germany, Spain, the United Kingdom, Japan, China, and South Korea, as well as other countries.

As FIGURE 12.8 shows, 20 percent of the electricity generated in the United States comes from nuclear energy. Early proponents of nuclear energy in the 1950s and 1960s claimed that it would be “too cheap to meter,” meaning that it would be so inexpensive that there would be no point in trying to figure out how much each customer used. However, construction of new nuclear power plants became more and more expensive in the United States, in part because public protests, legal battles, and other delays increased the cost of construction. Public protests arose because of concerns that a nuclear accident would release radioactivity into the surrounding air and water. Other concerns included uncertainty about appropriate locations for radioactive waste disposal and fear that radioactive waste could fall into the hands of individuals seeking to make a nuclear weapon. By the 1980s, it had become prohibitively expensive—both monetarily and politically—to attempt to construct a new nuclear power plant.

There are currently 104 nuclear power plants in the United States—the same number as there were two decades ago. However, because of the relatively low CO\textsubscript{2} emissions associated with nuclear energy, there has been a resurgence of interest in constructing additional nuclear power plants. There are certainly CO\textsubscript{2} emissions related to mining, processing, and transporting nuclear fuel and constructing a nuclear power plant. However, these emissions are perhaps a few percent to 10 percent of those related to generating an equivalent amount of electricity from coal. Two major issues of environmental concern remain, however—the possibility of accidents and disposal of radioactive waste.

THE POSSIBILITY OF ACCIDENTS Two accidents contributed to the global protests against nuclear energy in the 1980s and 1990s. On March 28, 1979, at the Three Mile Island nuclear power plant in Pennsylvania, operators did not notice that a cooling water valve had been closed the previous day. This oversight led to a lack of cooling water around the reactor core, which overheated and suffered a partial meltdown. The reactor core was severely damaged, and a large part of the containment structure became highly radioactive. An unknown amount of radiation was released from the plant to the outside environment. A few thousand schoolchildren and pregnant women were evacuated from the area surrounding the plant by order of the governor of Pennsylvania. An estimated 200,000 other people chose to evacuate as well. A great
deal of anxiety and fear were experienced by residents of the area, especially as reports of a potentially explosive gas bubble in the containment structure were evaluated in the days following the accident. Although there has been no documented increase in adverse health effects in the area of the plant as a result of this accident, several investigators maintain that infant mortality rates and cancer rates increased in the following years. This nuclear reactor, one of two at the Three Mile Island nuclear facility, has not been used since the accident. The Three Mile Island event, compounded by the coincidental release of the film *The China Syndrome*, about safety violations and a near-catastrophic accident at a nuclear power plant, led to widespread public fear and anger in Pennsylvania and elsewhere.

A much more serious accident occurred on April 26, 1986, at a nuclear power plant in Chernobyl, Ukraine. The accident occurred during a test of the plant when, in violation of safety regulations, operators deliberately disconnected emergency cooling systems and removed the control rods. With no control rods and no coolant, the nuclear reactions continued without control, and the plant overheated. These “runaway” reactions led to an explosion and fire that damaged the plant beyond use. At the time of the accident, 31 plant workers and firefighters died from acute radiation exposure and burns; many more died later of related causes.

After the accident, winds blew radiation from the plant across much of Europe, where it contaminated crops and milk from cows grazing on contaminated grass. More than a hundred thousand people were evacuated from the area around Chernobyl. Estimates of health effects vary widely, in part because of the paucity of information provided by the Soviet government, but a U.S. National Academy of Sciences panel estimated that 4,000 additional cancer deaths (over and above the average number of expected deaths) would occur over the next 50 years among people who lived near the plant or worked on the cleanup. There have been approximately 5,000 cases of thyroid cancer, most of them nonfatal, among children who were younger than 18 at the time of the accident and lived near the Chernobyl plant. Thyroid cancer may be caused by the absorption of radioactive iodine, one of the radioactive elements emitted during the accident.

**RADIOACTIVE WASTE** Long after nuclear fuel can produce enough heat to be useful in a power plant, it continues to emit radioactivity. At this point, it is considered radioactive waste. Because radioactivity can be extremely damaging to living organisms, radioactive materials must be stored in special, highly secure locations.

The use of nuclear fuels produces three kinds of radioactive waste: high-level waste in the form of used fuel rods; low-level waste in the form of contaminated protective clothing, tools, rags, and other items used in routine plant maintenance; and uranium
mine tailings, the residue left after uranium ore is mined and enriched. Disposal of all three types is regulated by the government, but because it has the greatest potential impact on the environment, we will focus here on high-level radioactive waste. After a period of time, nuclear fuel rods become “spent”—not sufficiently radioactive to generate electricity efficiently. As we discussed in Chapter 2, each radioactive isotope has a specific half-life: the time it takes for one-half of its radioactive atoms to decay. Uranium-235 has a half-life of 704,000,000 years, which means that 704 million years from today, a sample of $^{235}$U will be only half as radioactive as it is today. In another 704 million years it will lose another half of its radioactivity, so it will be one-fourth as radioactive as it is today.

Radiation can be measured with a variety of units. A becquerel (Bq) measures the rate at which a sample of radioactive material decays. 1 Bq is equal to the decay of one atom per second. A curie, another unit of measure for radiation, is 37 billion decays per second. If a material has a radioactivity level of 100 curies and has a half-life of 50 years, the radioactivity level in 200 years will be

\[
\frac{200 \text{ years}}{50 \text{ years/half-life}} = 4 \text{ half-lives}
\]

100 curies $\rightarrow$ 50 curies (one half-life) $\rightarrow$ 25 curies (two half-lives) $\rightarrow$ 12.5 curies (three half-lives) $\rightarrow$ 6.3 curies (four half-lives)

You can gain more experience in working with these calculations in Do the Math “Calculating Half-Lives” below.

Spent fuel rods remain a threat to human health for 10 or more half-lives. For this reason, they must be stored until they are no longer dangerous. At present, nuclear power plants are required to store spent fuel rods at the plant itself. Initially, all fuel rods were stored in pools of water at least 6 meters (20 feet) deep. The water acts as a shield from radiation emitted by the rods. Currently, more than 100 sites around the country are storing spent fuel rods. However, some facilities have run out of pool storage and are storing them in lead-lined dry containers on land (FIGURE 12.19). Eventually, all of this material will need to be moved to a permanent radioactive waste disposal facility.
Disposing of radioactive waste is a challenge. It cannot be incinerated, safely destroyed using chemicals, shot into space, dumped on the ocean floor, or buried in an ocean trench because all of these options involve the potential for large amounts of radioactivity to enter the oceans or atmosphere. Therefore, at present, the only solution is to store it safely somewhere on Earth indefinitely. The physical nature of the storage site must ensure that the waste will not leach into the groundwater or otherwise escape into the environment. It must be far from human habitation in case of any accidents and secure against terrorist attack. In addition, the waste has to be transported to the storage site in a way that minimizes the risk of accidents or theft by terrorists.

**DO THE MATH**

**Calculating Half-Lives**

Strontium-90 is a radioactive waste product from nuclear reactors. It has a half-life of 29 years. How many years will it take for a quantity of strontium-90 to decay to \( \frac{1}{8} \) of its original mass?

It will take 29 years to decay to \( \frac{1}{2} \) its original mass; another 29 years to \( \frac{1}{4} \); another 29 years to \( \frac{1}{8} \); another 29 years to \( \frac{1}{16} \):

\[ 29 + 29 + 29 + 29 = 116 \text{ years} \]

**Your Turn:** You have 180 g of a radioactive substance. It has a half-life of 265 years. After 1,325 years, what mass remains?
In 1978, the U.S. Department of Energy began examining a site at Yucca Mountain, Nevada, 145 kilometers (90 miles) northwest of Las Vegas, as a possible long-term repository for the country’s spent nuclear fuel. The Yucca Mountain proposal has generated enormous protest and controversy. In 2006, the Department of Energy released a report confirming the soundness of the research supporting the Yucca Mountain site. However, a few years later, after a change in presidential administrations, the Yucca Mountain project was cancelled. Nuclear energy raises a unique question of sustainability. It is a source of electricity that releases much less CO₂ than coal, and none during electricity generation. But some argue that the use of a fuel that consistently generates large quantities of high-level radioactive waste is not a sustainable practice. Many critics of nuclear energy maintain that there will never be a safe enough place to store high-level radioactive waste.

12.5. Fusion Power

As we have seen, nuclear fission occurs when the nuclei of radioactive atoms are broken apart into smaller, lighter nuclei. Nuclear fusion, the reaction that powers the Sun and other stars, occurs when lighter nuclei are forced together to produce heavier nuclei. In the process, a great deal of heat is generated. The nuclear fusion reaction that is most promising for electricity generation is that of two hydrogen isotopes fusing together into a helium atom. As the reaction occurs, a small amount of mass is lost and an immense amount of energy is liberated. Nuclear fusion seems to promise a seemingly unlimited source of energy that requires only hydrogen as an input and produces relatively small amounts of radioactive waste. Unfortunately, creating fusion on Earth requires a reactor that will heat material to temperatures 10 times those in the core of the Sun. These temperatures make containment extremely difficult. So far, the most promising techniques have involved suspending superhot material in a magnetic field, but the amount of energy required is greater than the energy output. Most experts believe that it will be several decades, or perhaps longer, before the promise of fusion power can be realized.

At present, our reliance on nuclear energy in the United States is subject to speculation and projections, but it is hard to know whether the positive aspects of nuclear energy will come to outweigh the risks of accidents and radioactive waste. Indeed, in 2006, applications for new nuclear power plants in the United States were filed with the Nuclear Regulatory Commission for the first time in more than two decades. Although no date for plant construction is yet certain, it does appear that some new nuclear power plants may come online in the United States before 2020.
TABLE 12.2 summarizes the major benefits and consequences of the conventional fuels we have discussed in this chapter.

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Pollutant and greenhouse gas emissions</th>
<th>Electricity (cents/kWh)</th>
<th>Energy return on energy investment*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil/ gasoline</td>
<td>Ideal for mobile combustion (high energy/mass ratio)</td>
<td>Significant refining required</td>
<td>Second highest emitter of CO₂ among fossil fuels</td>
<td>4.0 (gasoline)</td>
<td>5.7 (diesel)</td>
</tr>
<tr>
<td></td>
<td>Quick ignition/turn-off capability</td>
<td>Oil spill potential effect on habitats near drilling sites</td>
<td>Hydrocarbons Hydrogen sulfide</td>
<td></td>
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<tr>
<td></td>
<td>Cleaner burning than coal</td>
<td>Significant dust and emissions from fossil fuels used to power earth-moving equipment</td>
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<td></td>
<td></td>
<td>Human rights/ environmental justice issues in developing countries that export oil</td>
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<td></td>
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<td>Will probably be much less available in the next 40 years or so</td>
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<tr>
<td>Coal</td>
<td>Energy-dense and abundant—U.S. resources will last at least 200 years</td>
<td>Mining practices frequently risk human lives and dramatically alter natural landscapes</td>
<td>Highest emitter of CO₂ among energy sources</td>
<td>5 cents/kWh</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>No refining necessary</td>
<td>Coal power plants are slow to reach full operating capacity</td>
<td>Sulfur Trace amounts of toxic metals such as mercury</td>
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<td></td>
<td>Easy, safe to transport</td>
<td>A large contributing factor to acid rain in the United States</td>
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<td></td>
<td>Economic backbone of some small towns</td>
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<td></td>
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</tr>
<tr>
<td>Natural gas</td>
<td>Cogeneration power plants can have efficiencies up to 60 percent</td>
<td>Risk of leaks/explosions Twenty-five times more effective as a greenhouse gas than CO₂ Not available everywhere because it is transported by pipelines</td>
<td>Methane Hydrocarbons Hydrogen sulfide</td>
<td>8–10 cents/kWh</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Efficient for cooking, home heating, etc. Fewer impurities than coal or oil</td>
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<td></td>
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</tr>
<tr>
<td>Nuclear energy</td>
<td>Emits no CO₂ once plant is operational Offers independence from imported oil</td>
<td>Very unpopular; generates protests Plants are very expensive to build because of legal challenges Meltdown could be catastrophic Possible target for terrorist attacks</td>
<td>Radioactive waste is dangerous for hundreds of thousands of years No long-term plan currently in place to manage radioactive waste No air pollution during production</td>
<td>12–15 cents/kWh</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>High energy density, ample supply</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* Estimates vary widely.

**CHECKPOINT**

- How does a nuclear reactor work, and what makes it a desirable energy option?
- What are the two major concerns about nuclear energy?
- What are the promising aspects of and problems with nuclear fusion?

**WORKING TOWARD SUSTAINABILITY**

Meet TED: The Energy Detective
It is generally accepted that peer pressure influences behavior. When hotels placed small signs in the bathrooms telling their guests that other guests were reusing towels—rather than insisting on receiving fresh clean towels each day—the need for towel laundering dropped drastically. Many studies have shown that when people receive feedback about their electricity consumption, they will often respond just as the hotel guests did. A number of electric companies have experimented with mailings that show homeowners how much electricity they use in comparison to neighbors in similar-sized homes. However, if homeowners use less electricity than their neighbors, they may not be inclined to reduce their use further.

For decades, environmentalists have dreamed about a magical device that could allow homeowners to receive an instantaneous reading of actual electricity use in the home. Today, environmental scientists have produced such a device. The Energy Detective (TED) provides a readout on a small device that can sit on the kitchen table or be viewed on a laptop computer. And there are many other similar devices and software packages available, including Google Power Meter, which allows you to view your home electricity use on a laptop over the Internet (FIGURE 12.20).

![Home Electricity Use Diagram](image_url)

**Figure 12.20** The Energy Detective and Google Power Meter. TED allows a user to instantaneously monitor electricity use in a home.

TED and other such electricity monitoring devices provide an instantaneous readout of electricity use in your home. Suppose you are getting ready to head out for the evening. The refrigerator is plugged in, but is quiet, meaning that the compressor is not running at that exact moment. Before you turn out the last light and leave, you glance
at TED and see that your house is drawing 500 watts. Wait a minute, that’s not right! Then you remember that you left your Xbox 360 video game and 42-inch plasma TV screen on in the other room. You run over and turn them both off. TED now reads that only 45 watts are being used in your home. But if everything is turned off, why is your house using 45 watts? It’s probably due to the phantom load—unnecessary standby electricity—drawn by battery chargers, instant-on features on televisions, computers in sleep mode, and other electrical devices that are on even when you think they are off. Some TED owners have gone around their homes installing power strips that allow them to truly turn an appliance off and have seen their phantom loads drop as a result. Since we know that all electricity use has environmental implications, a reduction in electricity use by any means is beneficial. The reductions that come from simple changes in behavior are some of the easiest to achieve.

References

Key Ideas Revisited
- Describe how energy use and energy resources have varied over time, both in the United States and worldwide.

Energy use changes over time with the level of industrial development. The United States and the rest of the developed world have moved from a heavy reliance on wood and coal to fossil fuels and nuclear energy. The developing world still relies largely on wood, charcoal, and animal waste. Each source of energy is best suited for certain activities, and less well suited for others.

- Compare the energy efficiencies of the extraction and conversion of different fuels.

Energy efficiency is an important consideration in determining the environmental impacts of energy use. In general, the energy source that entails the fewest conversions from its original form to the end use is likely to be the most efficient. Although multi-passenger transportation is the most energy-efficient way to travel, in the United States the single-passenger vehicle is the most popular.

- Explain the various means of generating electricity.

Electricity generation plants convert the chemical energy of fuel into electricity. Coal, oil, natural gas, and nuclear fuels are the energy sources most commonly used for generating electricity. The electrical grid is a network of
interconnected transmission lines that ties power plants together and links them with end users of electricity.

- **Discuss the uses and consequences of using coal, oil, natural gas, and nuclear fuels.**

Coal is an energy-dense fossil fuel that is a common energy source for electricity generation. Coal combustion, however, is a major source of air pollution and greenhouse gas emissions. Petroleum includes both crude oil and natural gas. The United States uses more petroleum than any other fuel, primarily for transportation. Petroleum produces air pollution as well as greenhouse gas emissions. Oil spills are a major hazard to organisms and habitat. Natural gas is a relatively clean fossil fuel. Nuclear energy is a relatively clean means of electricity generation, though fossil fuels are used in constructing nuclear power plants and mining uranium. The major environmental hazards of nuclear energy are accidents and radioactive waste.

- **Describe projections of future supplies of our conventional energy resources.**

Fossil fuels are a finite resource. Most observers believe that oil production will begin to decline some time in the next few decades. The transition away from oil will have important environmental consequences, depending upon how quickly it occurs and whether we make a transition to renewable energy resources or alternative fossil fuels.

**PREPARING FOR THE AP EXAM**

**MULTIPLE-CHOICE QUESTIONS**

[Notes/Highlighting]

1. Which of the following is *not* a nonrenewable energy resource?
   - (a) Oil
   - (b) Coal
   - (c) Natural gas
   - (d) Wind
   - (e) Nuclear fuels
   **[Answer Field]**

2. The fact that global transfer of energy from fuels to electricity is about 35 percent efficient is mostly a consequence of
   - (a) the Hubbert curve.
   - (b) the law of conservation of matter.
   - (c) the first law of thermodynamics.
   - (d) the second law of thermodynamics.
   - (e) the law of limiting factors.
   **[Answer Field]**
3. Which of the following is the most fuel-efficient mode of transportation in terms of joules per passenger-kilometer?
   • (a) Train
   • (b) Bus
   • (c) Airplane
   • (d) Car with one passenger
   • (e) Car with three passengers
   [Answer Field]

4. Which of the following is not associated with the surface extraction of coal?
   • (a) Low death rates among miners
   • (b) Land subsidence and collapse
   • (c) Large piles of tailings
   • (d) Underground tunnels and shafts
   • (e) Acid runoff into streams
   [Answer Field]

5. Which of the following statements regarding petroleum is correct?
   • I It is formed from the decay of woody plants.
   • II It contains natural gas as well as oil.
   • III It migrates through pore spaces in rocks.
   • (a) I, II, and III
   • (b) I and III
   • (c) II only
   • (d) I and II
   • (e) II and III
   [Answer Field]

6. Nuclear power plants produce electricity using energy from the radioactive decay of
   • (a) uranium-235.
   • (b) uranium-238.
   • (c) uranium-239.
   • (d) plutonium-235.
   • (e) plutonium-238.
   [Answer Field]

7. Currently, most high-level radioactive waste from nuclear reactors in the United States is
   • (a) stored in deep ocean trenches.
   • (b) buried in Yucca Mountain.
   • (c) reprocessed into new fuel pellets.
   • (d) chemically modified into safe materials.
   • (e) stored at the power plant that produced it.
[Answer Field]
8. A radioactive isotope has a half-life of 40 years and a radioactivity level of 4 curies. How many years will it take for the radioactivity level to become 0.25 curies?
   • (a) 80
   • (b) 120
   • (c) 160
   • (d) 200
   • (e) 240

[Answer Field]
9. Which of the following energy sources is responsible for the largest fraction of electricity generation in the United States?
   • (a) Natural gas
   • (b) Coal
   • (c) Uranium
   • (d) Oil
   • (e) Wood

[Answer Field]
10. In 1969, M. King Hubbert published a graph known as the Hubbert curve. This graph shows
   • (a) the amount of nuclear fuel available in North America.
   • (b) the amount of nuclear fuel available in the world.
   • (c) the point at which world oil production will reach a maximum and the point at which we will run out of oil.
   • (d) the point at which world oil production will increase.
   • (e) the coal reserves found in the United States, China, and Russia.

FREE-RESPONSE QUESTIONS

[Notes/Highlighting]
1. Many college students have a mini fridge in their dorm room. A standard mini fridge costs roughly $100, uses about 100 watts of electricity, and can be expected to last for 5 years. The refrigerator is plugged into an electrical socket 24 hours a day, but is usually running only about 12 hours a day. Assume that electricity costs $0.10/kWh.
   • (a) Calculate the lifetime monetary cost of owning and operating the refrigerator. (2 points)
   • (b) Assume that the electricity used to power the refrigerator comes from a coal-burning power plant. One metric ton of coal contains 29.3 GJ(8,140 kWh) of energy. Because of the inefficiency of electricity generation and transmission, only
one-third of the energy in coal reaches the refrigerator. How many tons of coal are used to power the refrigerator during its lifetime? (2 points)

- (c) Assume that 15 percent of the mass of the coal burned in the power plant ends up as coal ash, a potentially toxic mixture that contains mercury and arsenic. How many tons of coal ash are produced as a result of the refrigerator’s electricity use over its lifetime? (2 points)

- (d) What externalities does your answer from part (a) not include? Describe one social and one environmental cost associated with using this appliance. (2 points)

- (e) Describe two ways a college student could reduce the electricity use associated with having a mini fridge in his or her dorm room. (2 points)

**Answer Field**

2. A number of U.S. electric companies have filed applications with the Nuclear Regulatory Commission for permits to build new nuclear power plants to meet future electricity demands.

- (a) Explain the process by which electricity is generated by a nuclear power plant. (2 points)

- (b) Describe the two nuclear accidents that occurred in 1979 and 1986, respectively, that led to widespread concern about the safety of nuclear power plants. (2 points)

- (c) Discuss the environmental benefits of generating electricity from nuclear energy rather than coal. (2 points)

- (d) Describe the three types of radioactive waste produced by nuclear power plants and explain the threats they pose to humans. (2 points)

- (e) Discuss the problems associated with the disposal of radioactive waste and outline the U.S. Department of Energy’s proposal for its long-term storage. (2 points)

**MEASURING YOUR IMPACT**

1. **Choosing a Car: Conventional or Hybrid?** One person buys a compact sedan that costs $15,000 and gets 20 miles per gallon. Another person pays $22,000 for the hybrid version of the same compact sedan, which gets 50 miles per gallon. Each owner drives 12,000 miles per year and plans on keeping the vehicle for 10 years.

- (a) A gallon of gas emits 20 pounds of CO$_2$ when burned in an internal combustion engine. The average cost of a gallon of gas over the 10-year ownership period is $3.00.
  - (i) Calculate how many gallons of gas each vehicle uses per year.
o (ii) Calculate the cost of the gas that each vehicle uses per year.

o (iii) Calculate the amount of CO\textsubscript{2} that each vehicle emits per year.

- (b) Based on your answers to questions i--iii, complete the data table below.

<table>
<thead>
<tr>
<th>Year of operation</th>
<th>Sedan: total costs—purchase and gas ($)</th>
<th>Sedan: cumulative CO\textsubscript{2} emissions (pounds)</th>
<th>Hybrid: total costs—purchase and gas ($)</th>
<th>Hybrid: cumulative CO\textsubscript{2} emissions (pounds)</th>
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</table>

- (c) Use the data in the table to answer the following questions:

  o (i) Estimate how many years it would take for the hybrid owner to recoup the extra cost of purchasing the vehicle based on savings in gas consumption.

  o (ii) After the amount of time determined in (i), compare and comment on the total costs (purchase and gas) for each vehicle at that time.

  o (iii) Over the 10-year ownership period, which vehicle is the more economically and environmentally costly to operate (in terms of dollars and CO\textsubscript{2} emissions), and by how much?

- (d) Suggest ways that the owner of the conventional car could reduce the overall yearly CO\textsubscript{2} emissions from the vehicle.

- (e) Suggest ways that the hybrid owner could become carbon-neutral in terms of operating the vehicle.