CHAPTER 13 Energy

Concentrating solar power (CSP) plants in desert regions could supply more electricity than all current world use.

LEARNING OUTCOMES

After studying this chapter, you should be able to answer the following questions:

- What are our dominant sources of energy?
- What is peak oil production? Why is it hard to evaluate future oil production?
- How important is coal in domestic energy production?
- What are the environmental effects of coal burning?
- How do nuclear reactors work? What are some of their advantages and disadvantages?
- What are our main renewable forms of energy?
- Could solar, wind, hydropower, and other renewables eliminate the need for fossil fuels?
- What are photovoltaic cells, and how do they work?
- What are biofuels? What are arguments for and against their use?

CASE STUDY

Renewable Energy in Europe

Northern Europe has a problem. They'd like to be environmentally responsible and wean themselves away from fossil fuels. Coastal regions generally have good wind power resources, and Great Britain, Germany, the Netherlands, and Scandinavia lead the world in offshore wind farms. But the most abundant renewable energy supply—solar—is often sorely lacking in the notoriously dark, cloudy, northern regions. Look at the location of northern Europe on a globe. Stockholm, Oslo, and Helsinki, for example, are all at about the same latitude as Anchorage, Alaska.

A great solar resource exists, however, just across the Mediterranean Sea in the Sahara desert, where the skies are cloudless and the sun shines fiercely nearly every day. An area about 125 × 125 km—or about 0.3 percent of North Africa—receives enough sunlight to supply all the current electrical consumption in Europe. And high-voltage, direct-current (HVDC) transmission lines have advanced, so it's economically and technically feasible to ship electrical current from Africa to Europe. Transmission losses are only 3 percent per 1,000 km and add just 1–2 cents per kilowatt-hour, an insignificant amount when you consider that the fuel is free.

A consortium led by the German Aerospace Center has been studying this issue for a decade. Operating under the name Desertech, about a dozen German banks and energy companies, together with other interested parties in more than 20 countries, have begun building a giant network of renewable energy facilities and a HVDC supergrid they hope will eventually link Europe, the Middle East, and North Africa (EU-MENA) to make a significant contribution both to regional development and to combating global climate change.

Some three dozen concentrating solar power (CSP) plants, spread across North Africa and the Middle East, together with about 20 offshore wind farms, a dozen hydroelectric dams, and a few biomass or geothermal facilities (fig. 13.1) linked together by HVDC "electric highways" form the heart of this ambitious plan. We'll discuss details of CSP later in this chapter, but basically it captures solar energy to generate steam to produce electricity. This technology is already competitive with fossil fuels. In fact, in 2008, when oil hit $140 per barrel, CSP was less than half the price of an equivalent amount of oil energy.

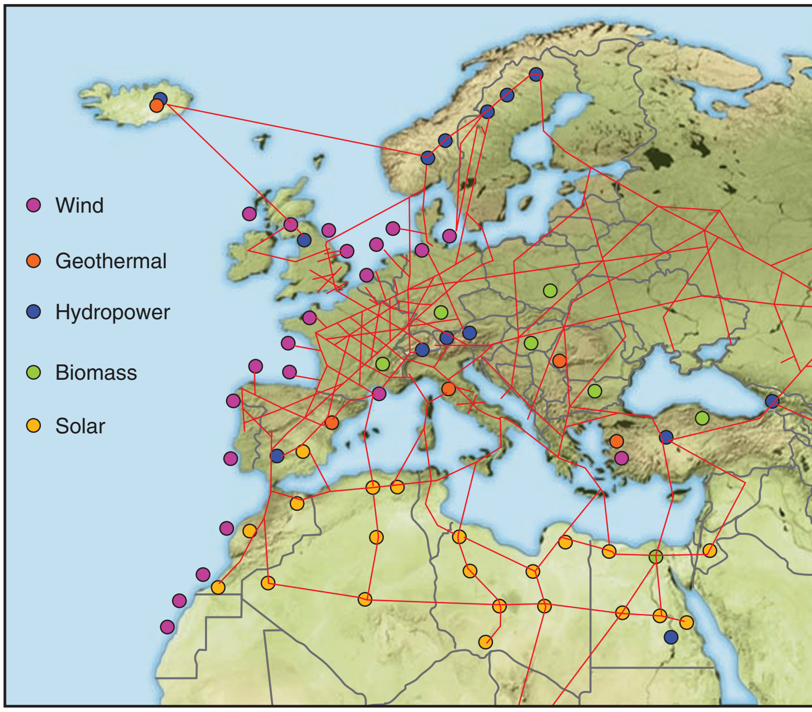
Why would oil-rich Arab countries want to help Europe kick their fossil fuel habit? Perhaps because the world is approaching—or may have already passed—peak oil production. And remaining supplies are becoming increasingly expensive and difficult to reach. Many formerly oil-rich countries are facing the prospect of life without oil. Why not sell an endless supply of solar power, and save your remaining oil for your own use or to sell for higher prices at a later date?

For Europe, wouldn't this just mean trading dependency on unstable Middle Eastern countries for oil to dependency on their solar electricity? Perhaps. But if Desertech leads to local economic development (it's expected that building and operating all those power plants will add 80,000 well- paying local jobs), and if local economies become dependent on the power and water from renewable energy, mutual benefits from the system may help make it safe from political threats and civil unrest.

The first steps in Desertech implementation are now taking place. In 2011, contracts were issued for 65 km of HVDC to connect Spain and France—the first link in the Supergrid. And at the same time, Morocco, which has been selected for the first CSP plant, announced it had chosen both the site for the facility and four consortia partners to design, finance, build, and operate it.

Many other parts of the world are following this development with interest. China, Australia, South Africa, and western North America also have vast solar potential. The Desertech Consortium points out that within 6 hours, world deserts receive more energy from the sun than humankind consumes in an entire year. Perhaps many others of us could benefit from a similar system.

In this chapter we'll look at our options for finding environmentally and socially sustainable ways to meet our energy needs. ■



▲ **FIGURE 13.1** A supergrid of HVDC transmission lines may link a network of renewable energy facilities in Europe, North Africa, and the Middle East and provide both a substantial percentage of electricity for the region as well as drinking water for desert nations. SOURCE: German Aerospace Center, 2010.

> *The stone age didn't end because we ran out of stones.*
>
> —SHEIK YAMANI, FORMER SAUDI OIL MINISTER

13.1 ENERGY RESOURCES AND USES

Using external energy sources is one of the main things that sets us apart from other species and makes us human. Fire was probably our first external energy source. We learned long ago to use fire to heat and light our encampments, cook our food, and keep predators at bay. At least 10,000 years ago, we domesticated animals and trained them to carry us and our belongings as well as to pull plows and carts. About the same time, we learned how to use wind and water power to move boats, grind grain, pump water, and do other useful tasks. When James Watt invented his steam engine 250 years ago, he unleashed an age of industrialization that greatly magnified our ability to transform our world.

The **fossil fuels**—coal, oil, and natural gas—that have powered the industrial age have brought us many benefits, but have also caused huge social, political, and environmental problems. As we discussed in chapter 9, perhaps the most threatening of these problems is that the burning of fossil fuels emits carbon dioxide (CO_2), which is changing our global climate. We now get nearly 90 percent of all commercial energy from fossil fuels. How we'll end our dependence on—some would say addiction to—fossil fuels is one of the most important problems that face us today. In this chapter we'll look at the costs and consequences of various energy sources as well as our options for the future. We'll start with the fossil fuels and nuclear power that provide most of our energy today, and then turn to renewable sources that could supply all the energy we will need in the not-too-distant future.

How do we measure energy?

To understand the magnitude of energy use, it is helpful to know the units used to measure it. **Work** is the application of force over distance, and we measure work in **joules** (table 13.1). **Energy** is the capacity to do work. **Power** is the rate of energy flow or the rate of work done: for example, one **watt** (W) is one joule per second. If you use a 100-watt light bulb for 10 hours, you have used 1,000 watt-hours, or one kilowatt-hour (kWh). Most American households use about 11,000 kWh per year (table 13.2).

TABLE 13.1 | Energy Units

1 joule (J) = work needed to accelerate 1 kg 1 m/sec^2 for 1 m (or 1 amp/sec flowing through 1 ohm resistance)

1 watt (W) = 1 J per second

1 terawatt (TW) = 1 trillion watts

1 kilowatt hour (kWh) = 1,000 W exerted for 1 hour (or 3.6 million J)

1 megawatt (MW) = 1 million (10^6) W

1 gigajoule (GJ) = 1 billion (10^9) J

1 standard barrel (bbl) of oil = 42 gal (160 liters)

TABLE 13.2 | Energy Uses

USES	kWh/YEAR*
Computer	100
Television	125
100 W light bulb	250
15 W fluorescent bulb	40
Dehumidifier	400
Dishwasher	600
Electric stove/oven	650
Clothes dryer	900
Refrigerator	1,100

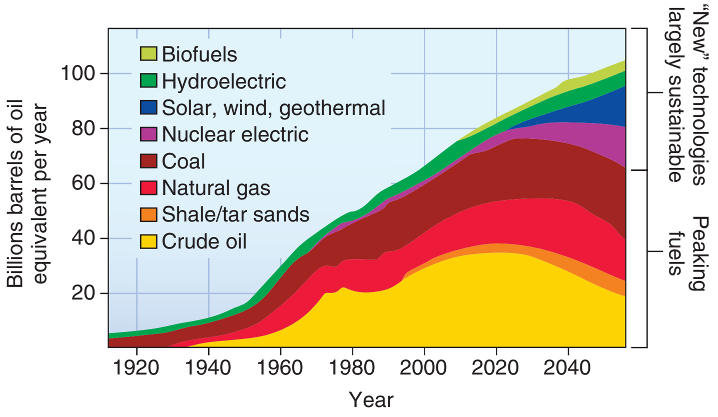
*Averages shown; actual rates vary greatly.

SOURCE: U.S. Department of Energy.

Fossil fuels supply most of our energy

Like most industrialized nations, the United States gets a vast majority of its energy from fossil fuels. According to the U.S. Energy Information Agency, oil currently provides 37 percent of this supply, followed by natural gas (25 percent) and coal (21 percent) (fig. 13.2). Renewables (hydro, wind, solar, biomass) provide 11 percent and nuclear power supplies 9 percent. In the twentieth century, although the rich countries of the world made up less than 5 percent of the total population, they consumed more than half the commercial energy. That situation is now changing, however. Rising incomes in China are leading to more energy consumption. China now consumes as much primary energy as all of Europe, and 85 percent as much as the United States. And because so much of China's energy comes from coal, it has now passed the United States in total CO_2 production.

How we, and the other countries of the world, can transition to sustainable energy is one of the most challenging issues we face. The scenario in figure 13.2 suggests that by 2050 we may be getting about one-quarter of our energy from renewables and another 15 percent or so from nuclear power. But many people



▲ **FIGURE 13.2** Fossil fuels, which now supply about 88 percent of all commerical energy in the world, are likely to decline as their costs increase and renewable energy gets cheaper.

believe that both fossil fuels and nuclear power are unacceptable, and that we should move much more quickly to renewables. Is that possible? As you'll learn in this chapter, there's more than enough energy from solar, wind, geothermal, and biomass power to provide everyone with a healthy, productive life.

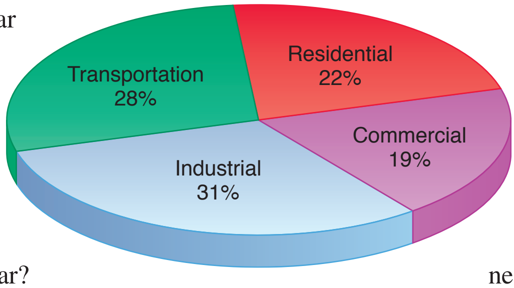


FIGURE 13.3 U.S. energy consumption by sector in 2012. SOURCE: U.S. EIA.

How much energy do you use every year? Most of us don't think about it much, but maintaining the lifestyle we enjoy requires an enormous energy input. On average, each person in the United States and Canada uses more than 300 gigajoules (GJ) (equivalent to about 60 barrels of oil) per year. By contrast, in some of the poorest countries of the world, such as Ethiopia, Nepal, and Bhutan, each person generally consumes less than 1 GJ per year. This means that each each U.S. citizen consumes, on average, almost as much energy in a single day as a person in one of these countries consumes in a year.

Clearly, energy consumption is linked to the comfort and convenience of our lives. Those of us in the richer countries enjoy many amenities not available to most people in the world. The link isn't absolute, however. Several European countries, including Sweden, Denmark, and Finland, have higher standards of living than does the United States by almost any measure but use about half as much energy.

How do we use energy?

The largest share of the energy used in the United States is consumed by industry (fig. 13.3). Mining, milling, smelting, and forging of primary metals consume about one-quarter of that industrial energy share. The chemical industry is the second largest industrial user of fossil fuels, but only half of that use is for energy generation. The remainder is raw material for plastics, fertilizers, solvents, lubricants, and hundreds of thousands of organic chemicals in commercial use.

Residential and commercial customers use roughly 41 percent of the primary energy consumed in the United States, mostly for space heating, air conditioning, lighting, and water heating. Transportation requires about 28 percent of all energy used in the United States each year, almost all of that comes from petroleum. About three-quarters of all transport energy is used by motor vehicles. Nearly 3 trillion passenger miles and 600 billion ton miles of freight are carried annually by motor vehicles in the United States. About 75 percent of all freight traffic in the United States is carried by trains, barges, ships, and pipelines, but because they are very efficient, they use only 12 percent of all transportation fuel.

Producing and transporting energy also consumes and wastes energy. About half of all the energy in primary fuels is lost during conversion to more useful forms, while being shipped to the site of end use, or during use. Electricity is generally promoted as a clean, efficient source of energy because, when it is used to run a resistance heater or an electrical appliance, almost 100 percent of its energy is converted to useful work and no pollution is given off.

What happens, however, before electricity reaches us? It takes large amounts of energy to mine, clean, and ship coal. Then nearly two-thirds of the energy in the coal we mine is lost in thermal conversion in the power plant. Finally, about 10 percent more is lost during conventional transmission and stepping down to household voltages. We need to take the whole fuel cycle into account when determining efficiency or the footprint of a particular source.

13.2 FOSSIL FUELS

Fossil fuels are organic (carbon-based) compounds derived from decomposed plants, algae, and other organisms buried in rock layers for hundreds of millions of years. Most of the richest deposits date to about 286 million to 360 million years ago (the Mississippian, Pennsylvanian, and Permian periods: see chapter 12), when the earth's climate was much warmer and wetter than it is now.

Coal resources are vast

World coal deposits are enormous, ten times greater than conventional oil and gas resources combined. Almost all the world's coal is in North America, Europe, and Asia (fig. 13.4), and just three countries, the United States, Russia, and China, account for two-thirds of all proven reserves. Coal seams can be 100 m thick and can extend across tens of thousands of square kilometers that were vast, swampy forests in prehistoric times. The total resource is estimated to be 10 trillion metric tons. If all this coal could be extracted, and we could find environmentally benign ways to use it, this would amount to several thousand years' supply. But do we really want to use all that coal? Coal mining is a dirty, dangerous activity. Underground mines are notorious for cave-ins, explosions, and lung diseases, such as black lung suffered by miners. Surface mines (called strip mines, where large machines scrape off overlying sediment to expose coal seams) are cheaper and generally safer for workers than tunneling, but leave huge holes where coal has been removed and vast piles of discarded rock and soil.

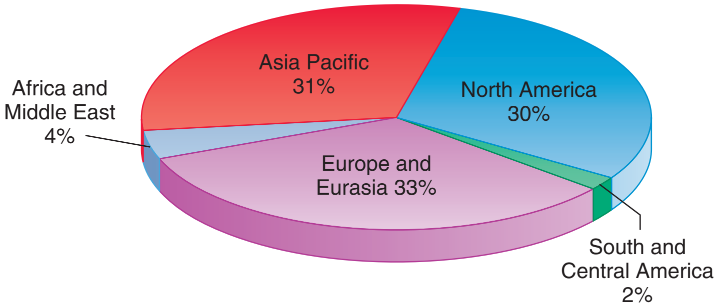


FIGURE 13.4 Proven-in-place coal reserves by region. SOURCE: U.S. CIA Factbook, 2012.

▲ FIGURE 13.5 One of the most environmentally destructive methods of coal mining is mountaintop removal. Up to 250 m of the mountain is scraped off and pushed into the valley below, burying forests, streams, farms, and sometimes whole towns.

An especially damaging technique employed in Appalachia is called mountaintop removal. Typically, the whole top of a mountain ridge is scraped off to access buried coal (fig. 13.5). In 2010 the EPA announced it would ban "valley fill," in which waste rock is pushed into nearby valleys, but existing operations are "grandfathered in" (see chapter 12 for further discussion). Mine reclamation is now mandated in the United States, but efforts often are only partially successful.

Coal burning releases huge amounts of air pollution. Every year the roughly 1 billion tons of coal burned in the United States (83 percent for electric power generation) releases close to a trillion metric tons of CO_2. This is about half of the industrial CO_2 released by the United States each year.

Coal also contains toxic impurities, such as mercury, arsenic, chromium, lead, and uranium, which are released into the air during combustion. The coal burned every year in the United States releases 18 million metric tons of sulfur dioxide (SO_2), 5 million metric tons of nitrogen oxides (NO_x), 4 million metric tons of airborne particulates, 600,000 metric tons of hydrocarbons and carbon monoxide, and 40 tons of mercury. This is about three-quarters of the SO_2 and one-third of the NO_x released by the United States each year. Sulfur and nitrogen oxides combine with water in the air to form sulfuric and nitric acids, making coal burning the largest single source of acid rain in many areas (chapter 9).

Most people aren't aware of it, but coal-burning plants emit radioactivity from uranium and thorium. You'd get more radioactivity living 70 years next to a coal power plant than next to a nuclear plant—assuming no accidents at the nuclear plant. It's possible to make either gas or liquid fuels out of coal, but these processes are even dirtier and more expensive than burning the coal directly. Both coal-to-liquid and coal-to-gas are environmentally disastrous.

Another problem with coal combustion was revealed in 2009 when an earthen dam broke in eastern Tennessee and released a billion gallons (3.8 billion liters) of coal ash sludge into a tributary of the Tennessee River. The ash contained dangerous levels of arsenic, mercury, and toxic hydrocarbons. After the spill, the U.S. EPA revealed that this impoundment was only one of hundreds of equally risky coal ash dumps across the country.

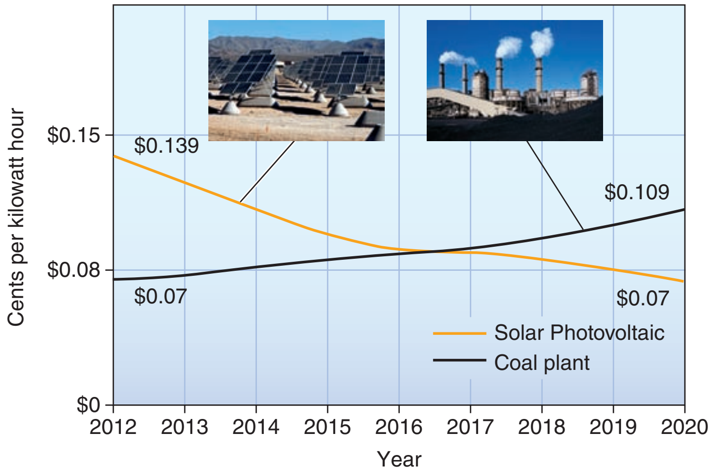
Coal may be on the way out

In 2010 the U.S. Energy Information Agency (EIA) predicted that coal would drop to 44 percent of America's electrical generation by 2035. Actually, we reached that level in 2011. Currently the government is projecting that coal will provide only 39 percent of our electricity by 2035, but that estimate appears to still be far too high. In reality, coal is fading quickly from our energy picture. Only half a dozen new coal-fired power plants are now under construction in the U.S. or in the planning stage. And when the last of those plants is finished about five years from now, no other new projects are proposed for the foreseeable future.

Federal regulations are part of this decline. The Mercury and Air Toxics Standards announced by the Environmental Protection Agency in 2012 will slash the allowable mercury emissions from coal-fired power plants. This was required by the 1970 Clean Air Act, but it was delayed for decades by owners of old power plants, who argued that their facilities were about to be closed anyway and so they shouldn't have to install expensive pollution control equipment. Forty years later, many of those plants are still in operation and still emitting dangerous pollutants.

The EPA estimates the new rules will cost utilities about \$9 billion, but will save \$90 billion in health care costs by 2016 by reducing our exposure to mercury, arsenic, chromium, and fine particulates that cause mental retardation, cardiovascular diseases, asthma, and other disorders. In 2012 the EPA also proposed limiting carbon emissions from power plants. If this rule goes into effect, new facilities will be allowed to emit no more than 1,000 lb (454 kg) of CO_2 per megawatt hour of electricity produced. Natural gas plants can easily meet that standard, but it's about half the amount released by the average coal-fired power plant. The only way to meet this limit with coal is to install expensive carbon capture and storage equipment.

Another problem for coal is that its prices are going up rapidly while solar costs are falling (fig. 13.6). By some accounts, solar, which cost almost twice as much as coal-fired electricity in 2012, could be one-third cheaper by 2020. One reason for this expected



▲ FIGURE 13.6 Solar electricity is becoming cost competitive with coal, and by 2020 solar should be cheaper than coal, experts predict.
SOURCE: Beyond Coal 2012.

price reversal is that solar panel prices fell by half in 2011 and are projected to come down more, while mercury limits and carbon-mitigation policies are driving up the price of coal.

Rapidly growing supplies and falling prices of natural gas also represent a challenge for coal. Gas is more versatile and cleaner burning than coal, but, as we'll discuss shortly, there are concerns that leakage from natural gas wells may negate its advantages.

There are cleaner ways to generate energy from coal. Gasification involves heating a coal slurry at high pressure in the presence of almost pure oxygen. The coal doesn't burn, instead it reacts with the oxygen and breaks down into a variety of gases, mostly hydrogen and carbon dioxide. The gases are cooled, separated, and purified of contaminants, such as sulfur, mercury, and arsenic. Carbon dioxide also can be captured and used for industrial processes or stored in geological formations. This technology has been proven in small-scale operations, but despite their enthusiasm for "Clean Coal," no utilities have opted for full-scale deployment. China claims to have about a dozen carbon-capture coal gasification plants, but observers report that although these facilities are capturing CO_2, none are actually storing it because they aren't required to by the central government. Instead, they simply vent it to the air.

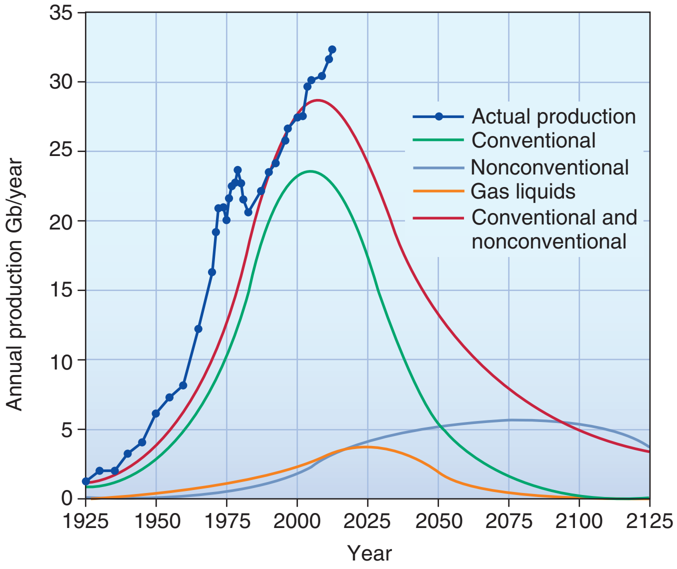
China and India, both of which have very large coal resources, now burn about half of all coal mined annually in the world. Both of these countries have been increasing coal production greatly in the recent past to fuel their rapidly growing economies. Continuing to do so could cause runaway global climate change, so it's good news that China, at least, seems determined to move quickly to renewable energy.

Have we passed peak oil?

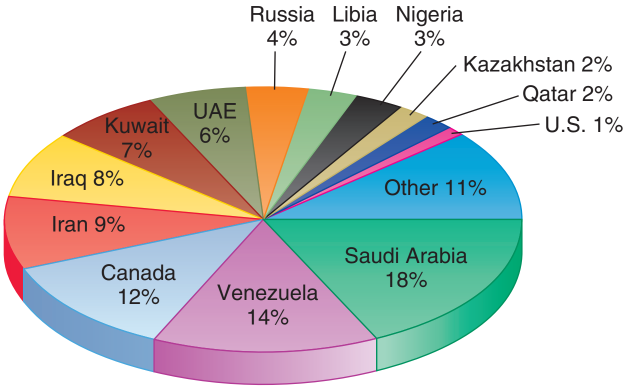
In the 1940s Dr. M. King Hubbert, a Shell Oil geophysicist, predicted that oil production in the United States would peak in the 1970s, based on estimates of U.S. reserves at the time. Hubbert's predicted peak was correct, and subsequent calculations have estimated a similar peak in global oil production in about 2005–2010 (fig. 13.7). Global production has not yet slowed significantly, but many oil experts expect that we will pass this peak in the next few years.

About half of the world's original 4 trillion bbl (600 billion metric tons) of liquid oil are thought to be ultimately recoverable. (The rest is too diffuse, too tightly bound in rock formations, or too deep to be extracted.) Of the 2 trillion recoverable barrels, roughly 1.26 trillion bbl are in proven reserves (commercially extractable using currently available technology). We have already used more than 0.5 trillion bbl—almost half of proven reserves—and the remainder is expected to last 41 years at current consumption rates of 30.7 billion bbl per year. Middle Eastern countries have more than half of the proven world supplies (fig. 13.8).

Consumption rates continue to climb, however, both in developed countries and in the fast-growing economies, such as China, India, and Brazil. China's energy demands have more than tripled in the past 35 years (much of this energy is used to produce goods for the U.S. and European markets), and China anticipates another doubling of energy demands in the next 15 years. Although renewables are supplying a growing share of China's energy, it's clear that competition is growing for global oil and gas supplies.



▲ **FIGURE 13.7** Worldwide production of crude oil with predicted Hubbert production. Gb = billion barrels. SOURCE: Jean Laherrère, www.hubbertpeak.org; International Energy Agency 2011.



▲ **FIGURE 13.8** Proven oil reserves. Twelve countries (7 of them in the Greater Middle East) account for 89 percent of all known, economically recoverable oil. Numbers add to more than 100 percent due to rounding. SOURCE: CIA Factbook, 2012.

Extreme oil and tar sands have extended our supplies

Estimates of our recoverable oil supplies have expanded dramatically as we've developed techniques for obtaining oil from ever-more extreme places. Some countries, such as Canada, which wasn't even in the list of top ten oil-rich countries, and Venezuela, which was only seventh a few years ago, have suddenly vaulted to second and third in terms of their proven oil reserves (see fig. 13.8). Even the United States, which has been an oil importer for decades, is producing more of its own oil. Still, just 12 countries control 88 percent of this strategic resource.

Most of us hadn't thought much about the dangers of deep ocean oil wells in remote places until the 2010 explosion and sinking of the *Deepwater Horizon* in the Gulf of Mexico (fig. 13.9).

▲ **FIGURE 13.9** In 2010, the oil drilling rig *Deepwater Horizon* exploded and sank, spilling 6 million barrels (800 million liters) of crude oil into the Gulf of Mexico. It was drilling in water 1 mile (1.6 km) deep, but other wells are now more than twice as deep.

▲ **FIGURE 13.10** Alberta tar sands are now the largest single source of oil for the United States, but water pollution, forest destruction, and the energy used to liquify the sticky tar are among the many costs of for extracting this oil.

At least 5 million barrels (800 million liters) of oil were spilled during the four months it took to plug the leak. The well was being drilled in about 1 mi deep (1.6 km) water, but that isn't very deep by current standards. For the Gulf of Mexico, the current record is held by the Perdido Spar rig, which is drilling in more than 3,000 m (9,627 ft) of water and then to a depth of more than 6 km below the seafloor. Brazil is drilling at a similar depth about 300 km (186 mi) offshore. This ultradeep deposit, which Brazil estimates could hold 50 to 100 billion barrels, could make that country fifth or sixth in the world in oil resources.

By some estimates, Venezuela could have more than 300 billion barrels of oil (more even than Saudi Arabia) accessible with current technology, but much of Canada's and Venezuela's new oil resources are from tar sands. Canadian deposits in northern Alberta are estimated to be equivalent to 1.7 trillion bbl of oil, and Venezuela has nearly as much. Together these deposits are three times as large as all conventional liquid oil reserves. **Tar sands** are composed of sand and shale particles coated with bitumen, a viscous mixture of long-chain hydrocarbons. Shallow tar sands are excavated and mixed with hot water and steam to extract the bitumen. For deeper deposits, superheated steam can be injected to melt the bitumen, which is then pumped to the surface like liquid crude. Once the oil has been retrieved, it still must be cleaned and refined to be useful. Depending on how much energy is used to extract and refine oil from tar sands, this resource may emit more CO_2 than coal.

In 2012, Canada produced more than 3 million bbl per day, or twice the maximum projected output of the Arctic National Wildlife Refuge (ANWR). There are severe environmental costs, however, in producing this oil (fig. 13.10). A typical facility producing 125,000 bbl of oil per day creates about 15 million m^3 of toxic sludge, releases 5,000 metric tons of greenhouse gases, and consumes or contaminates billions of liters of water each year. Surface mining in Canada could destroy millions of hectares of boreal forest. Native Cree, Chipewyan, and Métis people worry about the effects on their traditional ways of life if forests are destroyed and wildlife and water are contaminated.

A battle over a proposed pipeline to carry tar-sands oil from mines in Alberta to Houston, Texas, has brought this fuel source to public attention. Supporters of the Keystone XL pipeline claimed it would bring energy security to the United States and provide 20,000 jobs. Opponents countered that the pipeline wouldn't help the United States very much because the oil would be shipped to Texas and sold abroad. This could raise U.S. oil prices rather than lower them. Critics also say that the pipeline supporters' estimates of job creation are not based just on pipeline workers but include everyone who would play a role supporting those workers. A more realistic number, according to opponents, is only 50 permanent jobs on the pipeline. Furthermore, a rupture in the Keystone pipeline could contaminate the Ogallala aquifer, which supplies drinking water and irrigation for much of the Great Plains.

TransCanada, the company behind the pipeline, is also pursuing a northern "Gateway" route that would cross the Canadian Rockies on its way to a terminal in the fjords of British Columbia's Great Bear Rainforest. First Nations people fear that heavy tanker traffic through the narrow, twisting fjords could result in another *Exxon Valdez*–size accident in this pristine wilderness. Pipelines carrying tar sands oil have a much higher rupture rate than those for conventional oil. The residual sand is more abrasive, the oil is more acidic and corrosive, and heavy oil must be heated to higher temperatures to be shipped, all making tar sands pipelines more accident prone.

The United States also has large supplies of unconventional oil. **Oil shales** are fine-grained sedimentary rock rich in solid organic material called kerogen. Like tar sands, the kerogen can be heated, liquefied, and pumped out like liquid crude oil. Oil shale beds up to 600 m (1,800 ft) thick underlie much of Colorado, Utah, and Wyoming. If these deposits could be extracted at a reasonable price and with acceptable environmental impacts, they might yield the equivalent of several trillion barrels of oil.

However, mining and extraction of oil shale—like tar sands—uses vast amounts of water (a scarce resource in the arid western United States), releases much more carbon dioxide than burning an equivalent amount of coal, and creates enormous quantities of waste. The rock matrix expands when heated, resulting in two or three times the volume that was dug out of the ground. Billions of dollars were spent in the 1980s on pilot projects to produce shale oil. When oil prices dropped, these schemes were abandoned. With rapidly rising crude oil prices in recent years, interest in this resource has rekindled. The Bureau of Land Management has just approved the first tar sands mine in the U.S. and has designated 1 million ha (2.5 million acres) for tar sands and oil shale production in western mountain states.

Natural gas is growing in importance

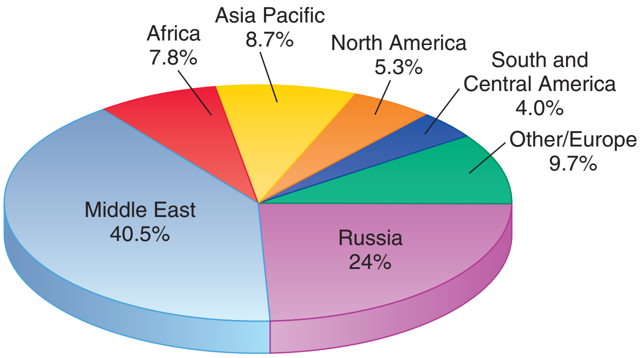
Natural gas (mostly methane) is the world's second-largest commercial fuel, making up about one-quarter of global energy consumption. Gas burns more cleanly than either coal or oil, and it generally produces only half as much CO_2 as an equivalent amount of coal. Many people hope that switching from coal to gas will help reduce global warming.

More than half of all the world's proven natural gas reserves are in the Middle East and the former Soviet Union (fig. 13.11). Both eastern and western Europe are highly dependent on imported gas. The total ultimately recoverable natural gas resources are thought to be 10,000 trillion ft^3, corresponding to about 80 percent as much energy as the estimated recoverable reserves of crude oil. The proven world reserves of natural gas are 6,200 trillion ft^3 (176 million metric tons). Because gas consumption rates are only about half of those for oil, current gas proven reserves represent roughly a 60-year supply at present usage rates.

Large amounts of methane are known to occur in many relatively shallow sedimentary beds. For the past decade or so, there has been intense drilling activity in the western United States. It often takes many closely spaced wells and directional drilling to extract methane from these "coal-bed" methane deposits. In Wyoming's Powder River basin, for example, 140,000 wells have been proposed for methane extraction. Together with the vast network of roads, pipelines, pumping stations, and service facilities, this industry is having serious impacts on ranching, wildlife, and recreation in formerly remote areas (fig. 13.12).

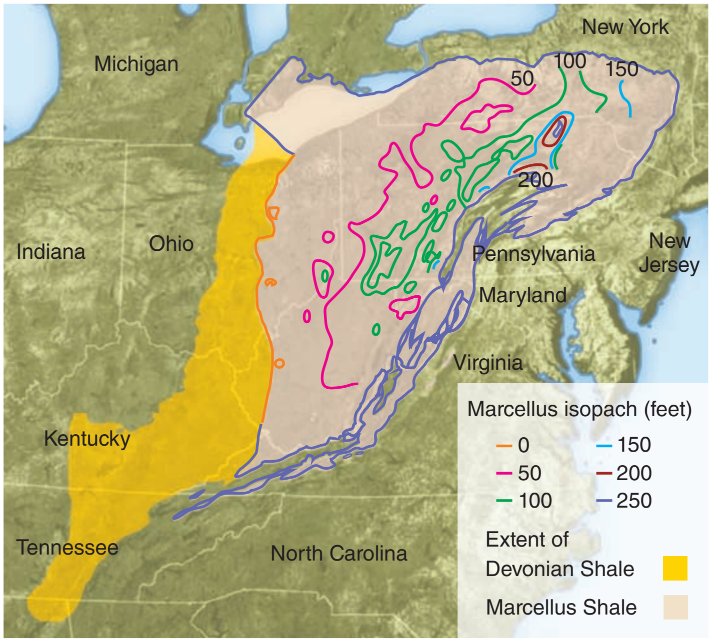
▲ **FIGURE 13.12** Some of the thousands of gas wells in the Jonah Field in Wyoming's Upper Green River Basin.

Now attention is shifting to eastern states. It has long been recognized that methane is present in the Marcellus and Devonian Shales, which underlie much of the Appalachian mountains (fig. 13.13), but the economically recoverable resource was thought to be relatively small. New drilling techniques, however, have now made this deposit a potentially "supergiant" gas field. The U.S. Geological Survey estimates that the Marcellus/Devonian formation may contain 500 trillion ft^3 (13 trillion m^3) of methane. If all of it were recoverable, it would make a 100-year supply for the United States at current consumption rates. Large amounts of gas now available have driven prices down sharply in recent years.



▲ **FIGURE 13.11** Proven natural gas reserves by region, 2011.

SOURCE: Data from British Petroleum, 2012.



▲ **FIGURE 13.13** The Marcellus and Devonian Shales, which underlie much of the Appalachian Mountain chain, contain a "supergiant" gas field.

But these shale deposits are generally "tight" formations through which gas doesn't flow easily. To boost well output, mining companies rely on hydraulic fracturing (or "fracking"). A mixture of water, sand, and various chemicals is pumped into the ground and rock formations at extremely high pressure. The pressurized fluid cracks sediments and releases the gas. Fracturing rock formations often disrupts aquifers, however, and contaminates water wells.

Drilling companies generally refuse to reveal the chemical composition of the fluids used in fracking. They claim it's a proprietary secret, but it's well known that a number of petroleum distillates, such as diesel fuel, benzene, toluene, xylene, polycyclic aromatic hydrocarbons, glycol ethers, as well as hydrochloric acid or sodium hydroxide, are often used. Many of these chemicals are known to be toxic to humans and wildlife. The U.S. EPA recently forced mining companies to reveal the contents, but not specific fractional composition, of their fracking fluids used on public land.

A study released in 2011 by the National Academy of Sciences reported that drinking water samples from shallow wells near methane drilling sites in Pennsylvania and New York had 17 times as much methane as those from sites far from drilling. And a study by researchers at Dartmouth concluded that 3.6 to 7.9 percent of the methane from shale-gas wells escapes to the atmosphere in leaks and venting over the life of the well. These methane emissions are up to twice those from conventional gas wells. Compared to coal, the climate footprint of shale gas is at least 20 percent greater for a comparable amount of energy, and may be twice as much over 100 years. This new gas supply may not help combat global climate change after all. Nevertheless, the U.S. EIA predicts that by 2020, about two-thirds of U.S. natural gas will come from shale beds and tight gas formations.

13.3 NUCLEAR POWER

In 1953 President Dwight Eisenhower presented his "Atoms for Peace" speech to the United Nations. He announced that the United States would build nuclear-powered electrical generators to provide clean, abundant energy. He predicted that nuclear energy would fill the deficit caused by predicted shortages of oil and natural gas. It would provide power "too cheap to meter" for continued industrial expansion of both the developed and the developing world. Today there are about 440 reactors in use worldwide, 104 of them in the United States. Half of the U.S. plants (52) are more than 30 years old and are approaching the end of their expected operational life (fig. 13.14). Cracking pipes, leaking valves, and other parts increasingly require repair or replacement as a plant ages. Nuclear power now amounts to about 9 percent of U.S. energy supply (almost twice the world average). All of it is used to generate electricity.

Rapidly increasing construction costs, safety concerns, and the difficulty of finding permanent storage sites for radioactive waste have made nuclear energy less attractive than promoters expected in the 1950s. Of the 140 reactors on order in 1975, 100 were subsequently canceled. The costs of decommissioning old reactors is a serious concern, because demolishing a worn-out plant may cost ten times as much as building it in the first place.

▲ **FIGURE 13.14** New York's Indian Point nuclear power plant is ranked the riskiest in the country by the U.S. Nuclear Regulatory Commission due to its age and location on the Hudson River just 24 miles (38 km) north of Manhattan Island. What would it cost to evacuate New York City if these reactors melt down?

Ten nuclear reactors have been shut down in the United States and deconstruction of most of them is now under way. Although these plants were generally small, costs have averaged several hundred million dollars each.

The nuclear power industry has been campaigning for greater acceptance, arguing that reactors don't release greenhouse gases that cause global warming. That's true during ordinary operation of the reactor, but the mining, processing, and shipping of nuclear fuel, together with decommissioning of old reactors and perpetual storage of wastes, result in up to 25 times more carbon emissions than an equal amount of wind energy.

Nevertheless, a number of prominent environmentalists have endorsed nuclear power as a solution to global climate change. In 2012 the Nuclear Regulatory Commission approved permits for two new nuclear reactors to be built in Georgia by the Southern Company. These reactors will be supported by $8 billion in loan guarantees from the federal government in addition to insurance caps on catastrophic accidents. If completed, these will be the first new nuclear power plants built in three decades in the United States.

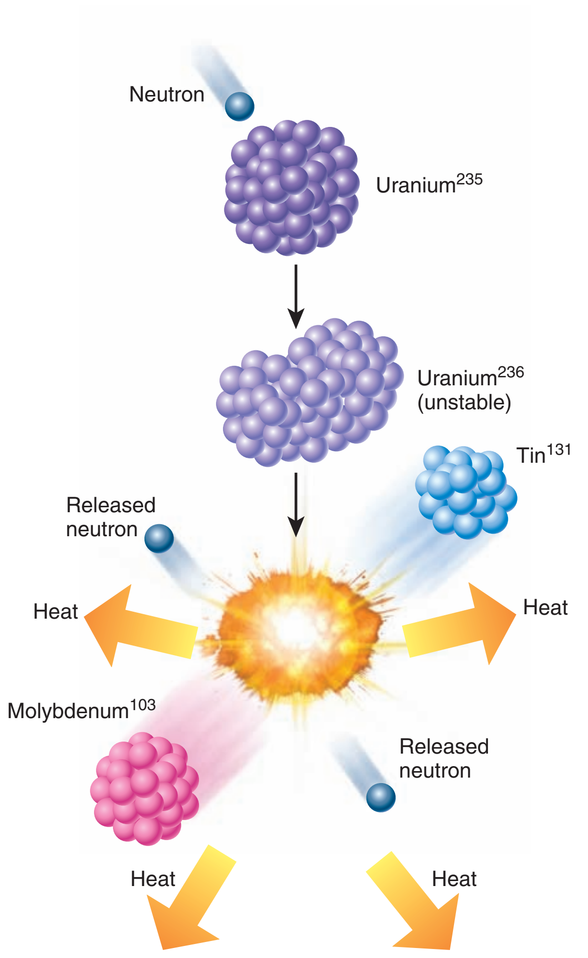
How do nuclear reactors work?

The most commonly used fuel in nuclear power plants is U^{235}, a naturally occurring radioactive isotope of uranium. Uranium ore must be purified to a concentration of about 3 percent U^{235}, enough to sustain a chain reaction in most reactors. The uranium is then formed into cylindrical pellets slightly thicker than a pencil and about 1.5 cm long. Although small, these pellets pack an amazing amount of energy. Each 8.5 g pellet is equivalent to a ton of coal or 4 bbl of crude oil.

The pellets are stacked in hollow metal rods approximately 4 m (13 ft) long. About 100 of these rods are bundled together to make a **fuel assembly**. Thousands of fuel assemblies containing about

100 tons of uranium are bundled in a heavy steel vessel called the reactor core. Radioactive uranium atoms are unstable—that is, when struck by a high-energy subatomic particle called a neutron, they undergo **nuclear fission** (splitting), releasing energy and more neutrons. When uranium is packed tightly in the reactor core, the neutrons released by one atom will trigger the fission of another uranium atom and the release of still more neutrons (fig. 13.15). Thus a self-sustaining **chain reaction** is set in motion, and vast amounts of energy are released.

The chain reaction is moderated (slowed) in a power plant by a neutron-absorbing cooling solution that circulates between the fuel rods. In addition, **control rods** of neutron-absorbing material, such as cadmium or boron, are inserted into spaces between fuel assemblies to shut down the fission reaction or are withdrawn to allow it to proceed. Water or some other coolant is circulated between the fuel rods to remove excess heat. The greatest danger in one of these complex machines is a cooling system failure. If the pumps fail or pipes break during operation, the nuclear fuel quickly overheats, and a "meltdown" can result that releases deadly radioactive material. Although nuclear power plants cannot explode like a nuclear bomb, the radioactive releases from a worst-case disaster, such as the meltdown of the Fukushima reactors in Japan in 2011, can entail enormous costs (see What Do You Think?, p. 312).



▲ FIGURE 13.15 The nuclear fission carried out in the core of a nuclear reactor. The unstable isotope uranium-235, absorbs a neutron and splits to form tin-131 and molybdenum-103. Two or three neutrons are released per fission event and continue the chain reaction. A tiny amount of mass is converted to energy (mostly heat).

Nuclear reactor design

Seventy percent of the world's nuclear plants are pressurized water reactors (PWR). Water circulates through the core, absorbing heat as it cools the fuel rods (fig. 13.16). This primary cooling water is heated to 317°C (600°F) and reaches a pressure of 2,235 psi. It then is pumped to a steam generator, where it heats a secondary water-cooling loop. Steam from the secondary loop drives a high-speed turbine generator that produces electricity. Both the reactor vessel and the steam generator are contained in a thick-walled, concrete-and-steel containment building that prevents radiation from escaping and is designed to withstand high pressures and temperatures in case of accidents.

Overlapping layers of safety mechanisms are designed to prevent accidents, but these fail-safe controls make reactors both expensive and complex. A typical nuclear power plant has 40,000 valves, compared with only 4,000 in a fossil fuel-fired plant of similar size. In some cases, the controls are so complex that they confuse operators and cause accidents rather than prevent them. Under normal operating conditions, however, a PWR releases very little radioactivity and is probably less dangerous for nearby residents than a coal-fired power plant.

We lack safe storage for radioactive waste

One of the most difficult problems associated with nuclear power is the disposal of wastes produced during mining, fuel production, and reactor operation. How these wastes are managed may ultimately be the overriding obstacle to nuclear power.

Enormous piles of mine wastes and abandoned mill tailings in uranium-producing countries represent another serious waste disposal problem. Production of 1,000 tons of uranium fuel typically generates 100,000 tons of tailings and 3.5 million liters of liquid waste. There now are approximately 200 million tons of radioactive waste in piles around mines and processing plants in the United States. This material is carried by the wind or washes into streams, contaminating areas far from its original source. Canada has even more radioactive mine waste on the surface than does the United States.

In addition to the leftovers from fuel production, the United States has about 77,000 tons of high-level (very radioactive) wastes. The high-level wastes consist mainly of spent fuel rods from commercial nuclear power plants and assorted wastes from nuclear weapons production. While they're still intensely radioactive, spent fuel assemblies are being stored in deep, water-filled pools at the power plants. These pools were originally intended only as temporary storage until the wastes were shipped to reprocessing centers or permanent disposal sites.

In 1987 the U.S. Department of Energy announced plans to build the first high-level waste repository in the desert under Yucca Mountain in Nevada. Waste was to be buried deep in the ground, where it was hoped it would remain unexposed

What Do YOU THINK?

Twilight for Nuclear Power?

On Friday, March 11, 2011, at 2:46 p.m. Tokyo time, a magnitude 9.0 earthquake hit northern Japan. The largest earthquake in Japan's recorded history damaged buildings and roads in its own right, but even worse, it generated tsunami waves up to 30 m (98 ft.) high that crushed buildings, toppled power lines, and washed away cars, boats, and millions of tons of debris. Authorities reported 15,846 deaths, 6,011 injuries, 3,320 people missing, and 125,000 buildings damaged or destroyed by waves.

Perhaps the worst result of this catastrophe was the destruction of four of the six nuclear reactors at the Fukushima Daiichi power station 170 mi (273 km) north of Tokyo. The reactors shut down, as they were designed to do, when the earthquake hit, but that eliminated the electricity needed to pump cooling water through the intensely hot reactor core. Backup generators and connections to the regional power grid that would have provided emergency power were destroyed by the tsunami. The reactors quickly overheated, and the fuel rods began to melt in three of the six reactors cores. Hydrogen explosions in the reactor buildings at the complex destroyed roofs and walls and scattered radioactive debris around the area. In addition, spent fuel rods in storage pools of two units also overheated and caught fire, releasing even more radiation.

The plant operators sprayed seawater onto reactors to cool the reactors and put out fires, but that washed radioactive pollution into the ocean and contaminated seafood on which Japan depends. In 2012 Japan began tunneling under the nuclear complex to install a giant concrete diaper to try to contain radioactive drainage from the site. High radioactivity caused authorities to order evacuation of 140,000 people living within a 12-mile (20 km) radius around the facility. But the toll could have been worse. If the melting fuel and fires hadn't been contained, the radiation release could have been ten times greater than the 1986 disaster at Chernobyl in Ukraine.

At one point, government officials seriously considered evacuating the Tokyo metropolitan area. That might have meant moving up to 40 million people, which would have been the largest mass relocation in world history. However, westerly winds blew most of the radiation out to sea and abandoning Tokyo wasn't necessary.

Still, cleanup will take decades, and some areas near the reactors may never be habitable again. Altogether, Japanese officials estimate that losses may be $300 (U.S.) billion. This disaster is causing people in many countries to reconsider nuclear power. In Japan, which once got about one-third of its electricity from nuclear plants and had plans to expand that share to more than half the nation's power supply, more than 80 percent of the population now say they are anti-nuclear. After the disaster, all the nation's 54 reactors were shut down. An intense debate occurred about whether to restart any of them.

▲ Three of the four nuclear reactors at Japan's Fukushima Diiachi that were destroyed by fuel melting and hydrogen explosions after the 2011 tsunami knocked out emergency cooling systems.

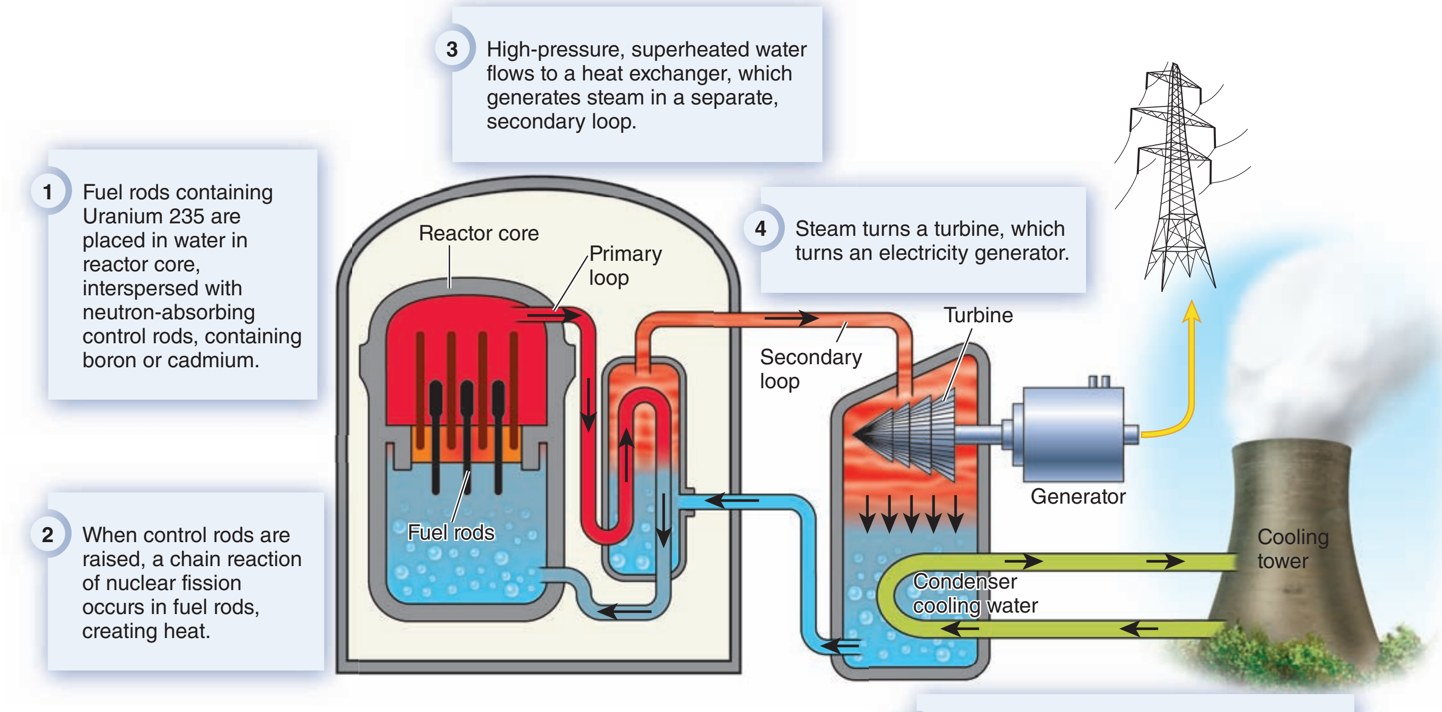
After Fukushima, Germany immediately shut down eight reactors and promised to close all the rest of its nuclear plants by 2022. China has suspended approvals for new reactors. Italy, Switzerland, and Spain voted to keep their countries nonnuclear. And in France, which gets three-quarters of its electricity from nuclear power, 62 percent of the population favored a phase-out of this energy source.

Could this be the death knell for nuclear power? Although public opinion swung strongly against this technology after Chernobyl, some people have been arguing that we need nuclear power at least as a temporary stopgap to replace fossil fuels in an effort to stop global climate change. What do you think? Are the risks of other disasters like Fukushima and Chernobyl worth the benefits of eliminating fossil fuels? And if we are going to make this Faustian bargain, what safeguards could we employ to reduce our risks?

to groundwater and earthquakes for the tens of thousands of years required for the radioactive materials to decay to a safe level. But continuing worries about the stability of the site led the Obama administration to cut off funding for the project in 2009 after 20 years of research and $100 billion in exploratory drilling and development.

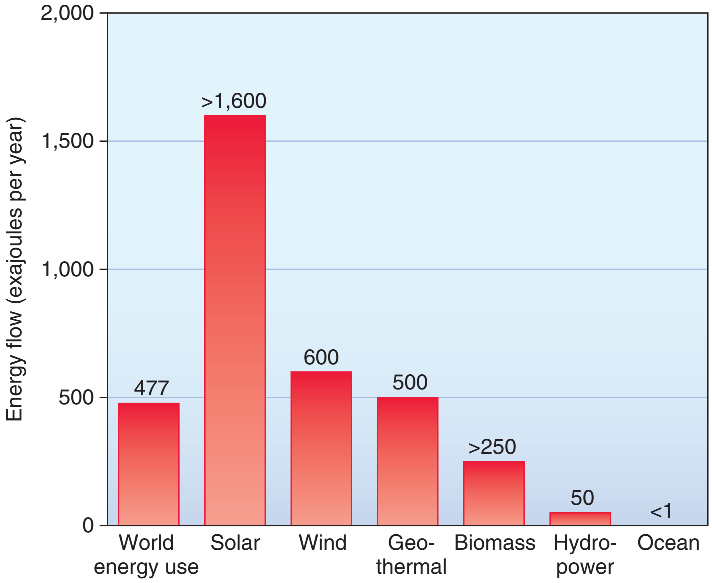
For the foreseeable future, the high-level wastes that were to go to Yucca Mountain will be held in large casks in temporary surface storage facilities located at 131 sites in 39 states (fig. 13.17). But local residents living near these sites fear casks will leak. Most nuclear power plants are built near rivers, lakes, or seacoasts. Radioactive materials could spread quickly over large areas if leaks occur. A hydrogen gas explosion and fire in 1997 in a dry storage cask at Wisconsin's Point Beach nuclear plant intensified opponents' suspicions about this form of waste storage.

If the owners of nuclear facilities had to pay the full cost for fuel, waste storage, and insurance against catastrophic accidents, no one would be interested in this energy source. Rather than be too cheap to meter, it would be too expensive to matter.



▲ **FIGURE 13.16** Pressurized water nuclear reactor. Water is superheated and pressurized as it flows through the reactor core. Heat is transferred to nonpressurized water in the steam generator, which drives the turbine to produce electricity.

▲ **FIGURE 13.17** Spent fuel is being stored temporarily in large, aboveground "dry casks" at many nuclear power plants.



▲ **FIGURE 13.18** Potential energy available from renewable resources using currently available technology in presently accessible sites. Together, these sources could supply more than six times current world energy use. SOURCE: Adapted from UNDP and International Energy Agency.

13.4 RENEWABLE ENERGY

In his 2011 State of the Union speech, President Barack Obama said, "To truly transform our economy, protect our security, and save our planet from the ravages of climate change, we need to ultimately make clean, renewable energy the profitable kind of energy. . . . So tonight, I challenge you to join me in setting a new goal: By 2035, 80 percent of America's electricity will come from clean energy sources." The good news is that using currently available technology and only those sites where energy facilities are socially, economically, and politically acceptable, there's more than enough renewable energy from the sun, wind, geothermal, biomass, and other sources to meet all our present energy needs (fig. 13.18).

One of the best ways to avoid energy shortages and to relieve environmental and health effects of our current energy technologies is simply to use less (see What Can You Do?, this page). Much of the energy we consume is wasted. Our ways of using energy are so inefficient that most potential energy in fuel is lost as waste heat, becoming a form of environmental pollution. Conservation involves technology innovation as well as changes in behavior, but we have met these challenges in the past.

Oil price shocks in the 1970s led to rapid improvements in industrial and household energy use. Although population and GDP have continued to grow since then, the **energy intensity**, or amount of energy needed to provide goods and services, has declined while prices have risen sharply. In response to federal regulations and high gasoline prices, average U.S. automobile fuel economy more than doubled from 13 mpg in 1975 to 28.8 mpg in 1988.

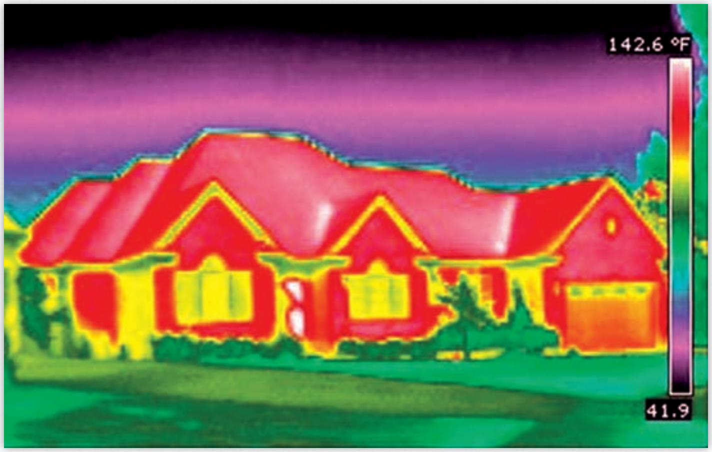
Unfortunately, an oil glut and falling fuel prices in the 1990s discouraged further conservation. In fact, over the next decade, average fuel economy decreased to only 20.4 mpg, or less than Henry Ford's Model T got nearly a century earlier. In 2012, however, the Obama administration announced a plan to increase national fuel economy standards to 54.5 miles per gallon by the year 2025. This will reduce U.S. oil consumption by 2.2 million barrels a day (see Active Learning, p. 315). But you don't have to wait until 2025. High-efficiency automobiles are already available. Low-emission, hybrid gas-electric vehicles get up to 72 mpg (30.3 km/l) on the highway. And walking, biking, or taking public transport can lower your personal energy footprint far more.

Many improvements in domestic energy efficiency also have occurred in recent decades. Today's average new home uses one-half the fuel required in a house built in 1974, but much more can be done. Reducing air infiltration is usually the cheapest, quickest, and most effective way of saving energy because it is the largest source of losses in a typical house. An energy audit can tell you where your greatest energy losses are (fig. 13.19). It doesn't take much skill or investment to caulk around doors, windows, foundation joints, electrical outlets, and other sources of air leakage. Mechanical ventilation is needed to prevent moisture buildup in tightly sealed homes. Household energy losses can be reduced by one-half to three-fourths by using better insulation, installing double- or triple-glazed windows, purchasing thermally efficient curtains or window coverings, and sealing cracks and loose joints.

What Can **YOU DO?**

Steps to Save Energy and Money

1. Live close to work and school, or near transit routes, so you can minimize driving.
2. Ride a bicycle, walk, and use stairs instead of elevators.
3. Keep your thermostat low in winter and high in summer. Fans are cheaper to run than air conditioners.
4. Buy fewer disposable items: producing and shipping them costs energy.
5. Turn off lights, televisions, computers, and other appliances when not needed.
6. Line-dry your laundry.
7. Recycle.
8. Cut back on meat consumption: if every American ate 20 percent less meat, we would save as much energy as if everyone used a hybrid car.
9. Buy local food (as much as possible) to reduce shipping energy.



▲ **FIGURE 13.19** Infrared photography shows heat loss in a building.

Green building can cut energy costs by half

Innovations in "green" building have been stirring interest in both commercial and household construction. Much of the innovation has occurred in large commercial structures, which have larger budgets—and more to save through efficiency—than most homeowners have. Elements of green building are evolving rapidly, but they include extra insulation in walls and roofs, coated windows to keep summer heat out and winter heat in, and recycled materials, which save energy in production (fig. 13.20). Orienting windows toward the sun, or providing roof overhangs for shade, are important for comfort as well as for saving money.

Many appliances, such as dishwashers and coffee makers, already have timers you can program to operate at specific times. Suppose your whole house or apartment had similar capacities. Several utilities are experimenting with **smart metering**, in which you get information not only on how much energy any particular appliance is using at a given time, but also the source of that energy and how much it costs. Using one of these systems, you might program your water heater to operate only after midnight when electricity is cheapest or surplus wind power is available. These systems can be controlled remotely. You might turn on your heating system or air conditioning with your telephone as you're on your way home. Or the utility might turn off those same systems for short periods to avoid bringing expensive peak power online.

New houses can also be built with extra-thick, superinsulated walls and roofs. Windows can be oriented to let in sunlight, and

Active LEARNING

Driving Down Gas Costs

Most Americans drive at least 1,000 miles per month in vehicles that get about 20 miles per gallon. Suppose gasoline costs $4.00 per gallon.

1. At these rates, how much does driving cost in a year? You can calculate the annual cost of driving with the following equation. Before multiplying the numbers, cross out the units that appear on both the bottom and the top of the fractions—if the units cancel out and give you $/year, then you know your equation is set up right. Then use a paper and pencil, and multiply the top numbers and divide by the bottom numbers. What is your annual cost?

$$\frac{12\text{ months}}{\text{year}} \times \frac{1{,}000\text{ mi}}{\text{month}} \times \frac{1\text{ gal}}{20\text{ mi}} \times \frac{\$4.00}{\text{gal}} =$$

2. Driving fast lowers your mileage by about 25 percent. At 75 mph, you get about three-fourths as many miles per gallon as you get driving 60 mph. This would drop your 20 mpg rate to 15 mpg. Recalculate the equation above, but replace the 20 with a 15. What is your annual cost now?
3. Efficiency also declines by about 33 percent if you drive aggressively, because rapid acceleration and braking cost energy. Aggressive driving would drop your 20 mpg mileage to about 13.4 mpg. How much would your yearly gas cost at 13.4 mpg?
4. In 2012, the Obama administration announced a goal of an average fleet efficiency of 54.5 mpg by 2025. How much would your yearly gas cost at 54.5 mpg? What is the difference between that cost and your cost at 20 mpg?

ANSWERS: 1. $2,400/year; 2. $3,200/year; 3. $3,592/year; 4. $881/year, or $1,519 less than at 20 mpg.

eaves can be used to provide shade. Double-glazed windows that have internal reflective coatings and that are filled with an inert gas (argon or xenon) have an insulation factor of R11, the same as a standard 4-inch-thick insulated wall, or ten times as efficient as a single-pane window. Superinsulated houses now being built in Sweden require 90 percent less energy for heating and cooling than the average American home. President Obama's "Cash for Caulkers" initiative planned to retrofit 100 million American homes and generate a million green jobs while cutting greenhouse gas emissions 5 percent over the next 20 years.

Improved industrial design has also cut our national energy budget. More efficient electric motors and pumps, new sensors and control devices, advanced heat-recovery systems, and material recycling have reduced industrial energy requirements significantly. In the early 1980s, U.S. businesses saved $160 billion per year through conservation. When oil prices collapsed, however, many businesses returned to wasteful ways.

Cities can make surprising contributions to energy conservation. New York City has become a leader in this effort, replacing 11,000 traffic signals with more-efficient LEDs (light-emitting diodes), and 180,000 old refrigerators with energy-saving models. Ann Arbor, Michigan, replaced 1,000 streetlights with LED models. These lights saved the city over $80,000 in the first year, and will pay for themselves in just over two years.

Cogeneration makes electricity from waste heat

One of the fastest growing sources of new energy is **cogeneration**, the simultaneous production of both electricity and steam or hot water in the same plant. By producing two kinds of useful energy in the same facility, the net energy yield from the primary fuel is increased from 30–35 percent to 80–90 percent. In 1900 half the electricity generated in the United States came from plants that also provided industrial steam or district heating. As power plants became larger, dirtier, and less acceptable as neighbors, they were forced to move away from their customers. Waste heat from the turbine generators became an unwanted pollutant to be disposed of in the environment. Furthermore, long transmission lines, which are unsightly and lose up to 20 percent of the electricity they carry, became necessary.

By the 1970s, cogeneration had fallen to less than 5 percent of our power supplies, but interest in this technology is growing. District heating systems are being rejuvenated, and the EPA estimates that cogeneration could produce almost 20 percent of U.S. electrical use, or the equivalent of 400 coal-fired plants.

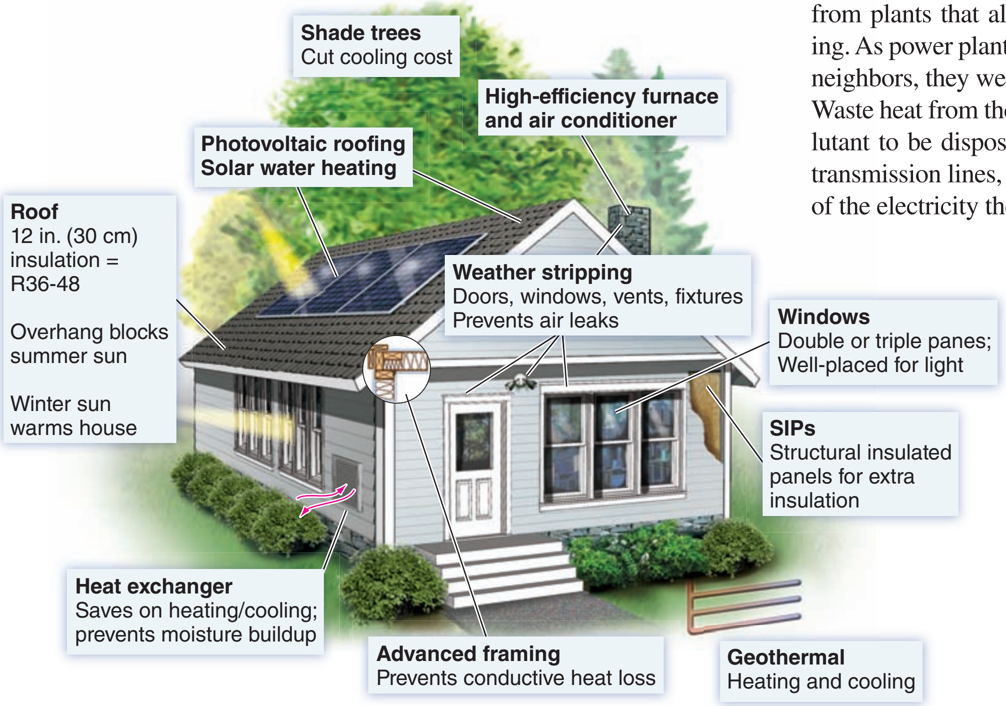


FIGURE 13.20 Energy-efficient buildings can lower energy costs dramatically. Many features can be added to older structures. New buildings that start with energy-saving features (such as SIPs or advanced framing) can save even more money.

13.5 ENERGY FROM BIOMASS

Plants capture immense amounts of solar energy by storing it in the chemical bonds of plant cells. Firewood is probably our first fuel source. As recently as 1850, wood supplied 90 percent of the heat used in the United States. For more than a billion people in developing countries, burning **biomass** (plant materials) remains the principal energy source for heating and cooking. An estimated 1,500 m^3 of fuelwood is gathered each year globally. This amounts to half of all wood harvested. Wood gathering and charcoal burning are important causes of deforestation in many rural areas. Providing efficient wood stoves can improve people's lives while also saving forests. In developed countries, where we depend on fossil fuels for most energy, wood burning is a minor heat source.

In developed countries, biomass burning can make a significant contribution to renewable energy supplies. Both agricultural wastes (such as straw and corn stalks) and biomass crops, such as reeds and elephant grass growing on land unsuitable for food crops, can be highly sustainable. These crops are carbon neutral because they absorb as much CO_2 in growing as they emit when burned.

Ethanol and biodiesel can contribute to fuel supplies

Biofuels, such as ethanol and biodiesel, are by far the biggest recent news in biomass energy. Globally, production of these two fuels is booming—from Brazil, which gets about 40 percent of its transportation energy from ethanol generated from sugarcane, to Southeast Asia, where millions of hectares of tropical forest have been cleared for palm oil plantations, to the United States, where about one-fifth of the corn (maize) crop currently is used to make ethanol. In 2009 President Obama proposed spending $150 billion over 10 years to develop renewable fuels and create 5 million "green collar" jobs. He proposed increasing ethanol production in the United States from 9 billion to 36 billion gallons per year (30 billion to 136 billion liters) by 2022. However, it would take the entire U.S. corn crop to produce that much ethanol from corn. We need to find other ways to create biofuels.

Crops with a high oil content, such as soybeans, sunflower seed, rape seed (usually called canola in America), and palm oil fruits are relatively easy to make into biodiesel. In some cases the oil needs only minimal cleaning to be used in a standard diesel engine. However, it would take a very large land area to meet our transportation needs with soy or sunflowers. Furthermore, diversion of these oils for vehicles deprives humans of important sources of edible oils.

Oil palms are considerably more productive per unit area than soy or sunflower (although palm fruit is more expensive to harvest and transport). Currently millions of hectares of species-rich forests in Southeast Asia are being destroyed to create palm oil plantations. Indonesia already has 6 million ha (15 million acres) of palm oil plantations, and Malaysia has nearly as much. Together these two countries produce nearly 90 percent of the world's palm oil.

Cellulosic ethanol may offer hope for the future

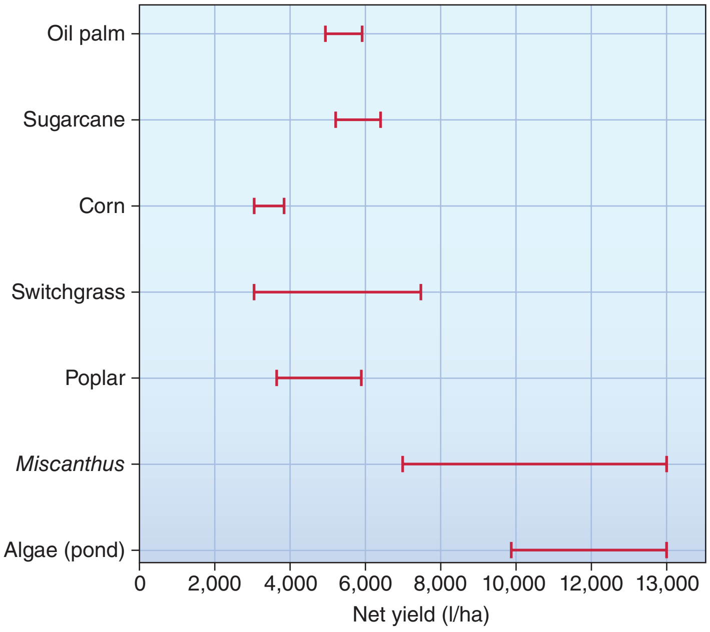
Crops such as sugarcane and sugar beets have a high sugar content that can be fermented into ethanol, but sugar is expensive and the yields from these crops are generally low, especially in temperate climates. Starches in grains, such as corn, have higher yields and can be converted into sugars that can be turned by yeast into ethanol or other alcohols. The idea of burning alcohol in vehicles isn't new. Henry Ford designed his 1908 Model T to run on ethanol.

Since 1980 more than 100 new refineries have been built, and U.S. ethanol production has grown from about 500 million liters to 30 billion liters per year. Most scientists calculate that corn ethanol contains only slightly more energy than you put into producing it, but everyone agrees that producing ethanol from **cellulosic** (woody) **crops** would have considerable environmental, social, and economic advantages over using edible grains or sugar crops for transportation fuel (fig. 13.21).

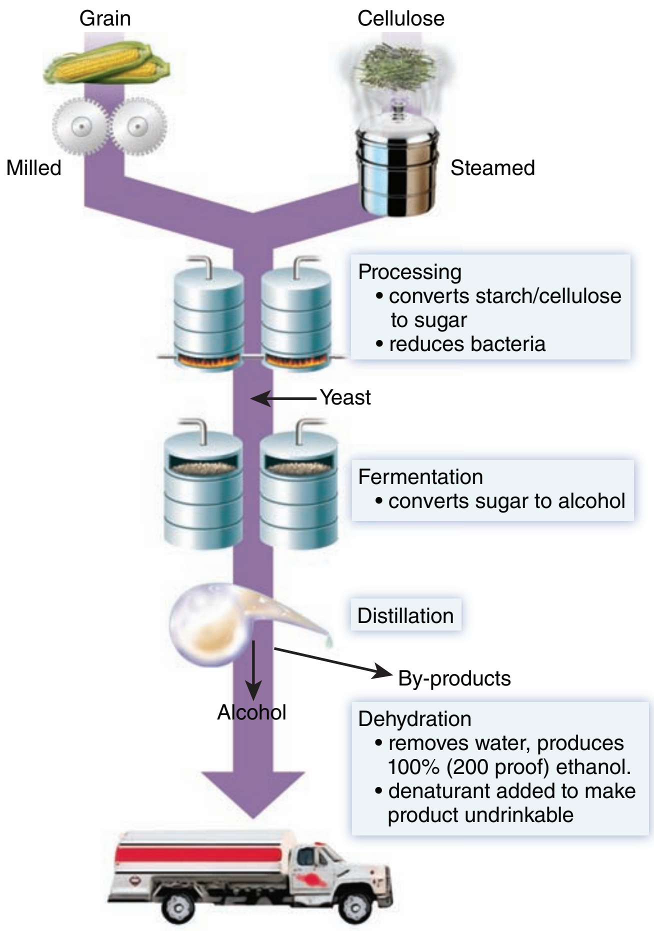
A number of techniques have been proposed for extracting sugars from cellulosic materials. Most involve mechanical chopping or shredding followed by treatment with bacteria or fungi to break down cellulose into soluble sugars (fig. 13.22).

So far, there are no commercial-scale cellulosic ethanol factories operating in North America, but the Department of Energy has provided $385 million in grants for six cellulosic biorefinery plants. These pilot projects will test a wide variety of feedstocks, including rice and wheat straw, milo stubble, switchgrass hay, almond hulls, corn stover (stalks, leaves, and cobs), and wood chips.

One of the most exciting biofuel crops is *Miscanthus x giganteus*, a perennial grass from Asia. Often called elephant grass (although this name is also used for other species), Miscanthus is a sterile, hybrid grass that grows 3 or 4 m in a single season



▲ **FIGURE 13.21** Proven biofuel sources include oil palms, sugarcane, and corn grain (maize). Other experimental sources may produce better yields, however. SOURCE: Data from E. Marris, 2006. *Nature* 444:670–678.



▲ FIGURE 13.22 Ethanol (or ethyl alcohol) can be produced from a wide variety of sources. Maize (corn) and other starchy grains are milled (ground) and then processed to convert starch to sugar, which can be fermented by yeast into alcohol. Distillation removes contaminants and yields pure alcohol. Cellulosic crops, such as wood or grasses, can also be converted into sugars, but the process is more difficult. Steam blasting, alkaline hydrolysis, enzymatic conditioning, and acid pretreatment are a few of the methods for breaking up woody material. Once sugars are released, the processes are similar.

▲ FIGURE 13.23 *Miscanthus x giganteus* is a perennial grass that can grow 3 or 4 m in a single season. It thrives on marginal land with little fertilizer or water and can produce five times as much biomass as corn.

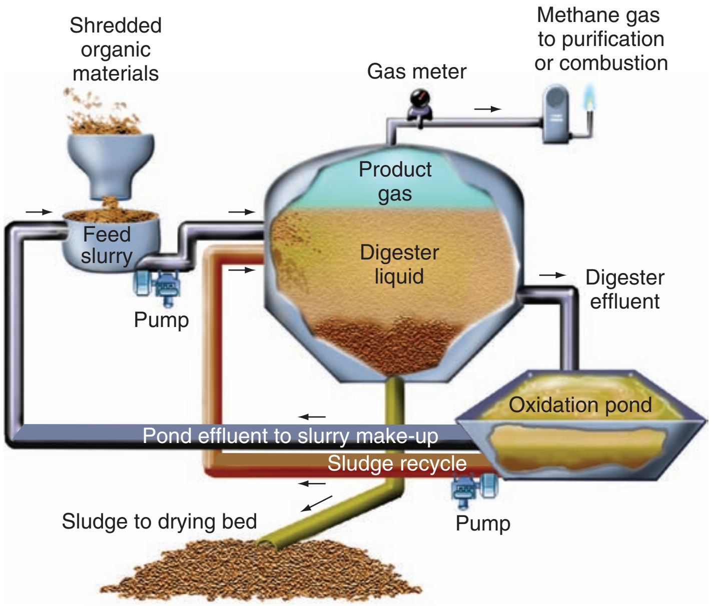
(fig. 13.23). Miscanthus can produce at least five times as much dry biomass per hectare as corn. Its perennial growth and long-lasting canopy also protect the soil from erosion and require much less fuel for cultivation.

Where using corn to produce enough ethanol to replace 20 percent of U.S. gasoline consumption would take about one-quarter of all current U.S. cropland out of food production, Miscanthus could produce the same amount on less than half that much area. And it wouldn't need to be prime farm fields. Miscanthus can grow on marginal soil with far less fertilizer than corn needs. In the fall, Miscanthus moves nutrients into underground rhizomes. This means that the standing stalks are almost entirely cellulose and next year's crop needs very little fertilizer.

Harvesting, storing, and shipping biomass crops remains a problem. The low energy content of straw or wood chips, compared to oils or sugars, makes it prohibitively expensive to ship them more than about 50 km (31 mi) to a refinery. We might need to have a very large number of small refineries if we depend on cellulosic ethanol. Interestingly, some authors claim that you could drive a hybrid automobile about twice as far on the electricity generated by burning a ton of dry biomass than you could on the ethanol fermented from that same ton. So, burning biomass may still be a better solution than fermentation if we have electric vehicles.

Methane from biomass is efficient and clean

Just about any organic waste, but especially sewage and manure, can be used to produce methane. Methane gas, the main component of natural gas, is produced when anaerobic bacteria (bacteria living in an oxygen-free space) digest organic matter (fig. 13.24).



▲ FIGURE 13.24 Continuous unit for converting organic material to methane by anaerobic fermentation. One kilogram of dry organic matter will produce 1–1.5 m^3 of methane, or 2,500–3,600 million calories per metric ton.

The main by-product of this digestion, CH_4, has no oxygen atoms because no oxygen was available in digestion. But this molecule oxidizes, or burns, easily, producing CO_2 and H_2O (water vapor). Consequently, methane is a relatively clean, efficient fuel. Today, as more cities struggle to manage urban sewage and feedlot manure, methane could be a rich source of energy. In China, in addition to solar and wind power, more than 6 million households use methane, also known as biogas, for cooking and lighting. Two large municipal facilities in Nanyang, China, for example, provide fuel for more than 20,000 families.

Methane is a promising resource, but it has not been adopted as widely as it could be. Gas is harder to store than liquid fuels like ethanol, and low prices for natural gas and other fuels have reduced incentives for building methane production systems. However, concerns about greenhouse gases may lead to further development, because methane is a powerful agent of atmospheric warming (chapter 9). Especially around livestock facilities, such as poultry or hog barns, large lagoons of liquid manure release a constant flow of methane to the atmosphere. These lagoons are also a threat to water bodies, because they occasionally overflow. But trapping this methane would provide energy, save money, and reduce atmospheric impacts. City sewage treatment plants and landfills also offer rich, and mostly untapped, potential for methane generation (chapter 14).

Could algae be a hope for the future?

Algae might be an even more productive biofuel crop than any we've discussed so far. While Miscanthus can yield up to 13,000 liters (3,500 gal) of ethanol per hectare, some algal species growing in a photobioreactor (high-tech greenhouse) might theoretically produce 30 times as much high-quality oil. This is partly because single-celled algae can grow 30 times as fast as higher plants. Furthermore, some algae store up to half their total mass as oil. Photobioreactors are much more expensive to build and operate than planting crops, but they could be placed on land unsuitable for agriculture and they could use recycled water. Open ponds are much cheaper than photobioreactors, but they also produce far less biomass per unit area. So far, the actual yield from algal growth facilities is actually about the same as Miscanthus.

One of the most intriguing benefits of algal growth facilities is that they could be placed next to conventional power plants, where CO_2 from burning either fossil fuels or biomass could be captured and used for algal growth. Thus they'd actually be carbon negative: providing a net reduction in atmospheric carbon while also creating useful fuel.

An algal bioreactor started producing biodiesel in South Africa in 2006, and one in Brazil aims to soon start trapping CO_2 from a coal-fired power plant. A number of U.S. companies, including Solix Biofuels, Sapphire Energy, OriginOil, PetroAlgae, and Shell Oil, are exploring algal biofuels. In 2009 Japan Airlines made a test flight using a combination of jet fuel and algal oils. Another tantalizing fact is that some algae produce hydrogen gas as a photosynthetic by-product. If fuel cells ever become economically feasible, algae might provide them with a energy source that doesn't depend on fossil fuels.

13.6 WIND AND SOLAR ENERGY

Renewable sources could supply all the energy we need (see Key Concepts, p. 320). Solar energy is our most abundant and ubiquitous renewable resource, followed by wind power. Engineering developments and mass production have brought prices for wind and solar down so they now compete with fossil fuels almost everywhere. Renewables provide more jobs, take less land, and keep more money at home, where it can benefit local communities rather than support dictatorial regimes in unstable countries as we now do with our payments for fossil fuels. Perhaps most important, wind and solar don't emit CO_2 that disrupts our global climate.

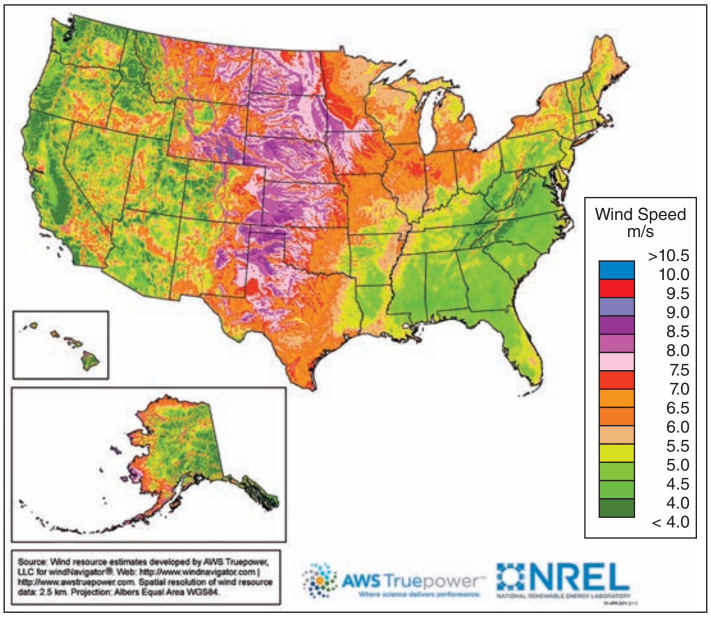
As the opening case study for this chapter shows, wind and solar energy can be tied together over a wide geographical area to create a steady, dependable, affordable electrical supply. Within 6 hours, deserts of the world receive more energy from the sun than humankind consumes within an entire year. If we can capture just a fraction of that energy, we could stop burning fossil fuels almost entirely. Wind has a number of advantages over most other power sources. Wind farms and solar collectors have much shorter planning and construction times than fossil fuel or nuclear power plants. Furthermore these renewable facilities are modular (a few or a lot more turbines or solar panels can be added if loads grow), and neither has ongoing fuel costs or air emissions.

Wind could meet all our energy needs

Wind power is the world's fastest-growing energy source and could replace all the commercial energy we now use. With 250,000 MW of globally installed capacity in 2012, wind power is producing about 500 TWhr of electricity annually. The Wind Energy Association predicts that 1.5 million MW of capacity could be possible by 2020.

China is now the world's largest producer of wind turbines. Clean technology provides more than 1 million Chinese jobs building equipment, much of which is exported. China now has at least 63 GW of wind power, or about one-quarter of the world total (fig. 13.25). The biggest wind turbines now being built have

▼ **FIGURE 13.25** China is now the world's largest producer of wind turbines and has about one-quarter of all installed wind power capacity. Together with solar, this clean technology provides more than 1 million jobs in China.



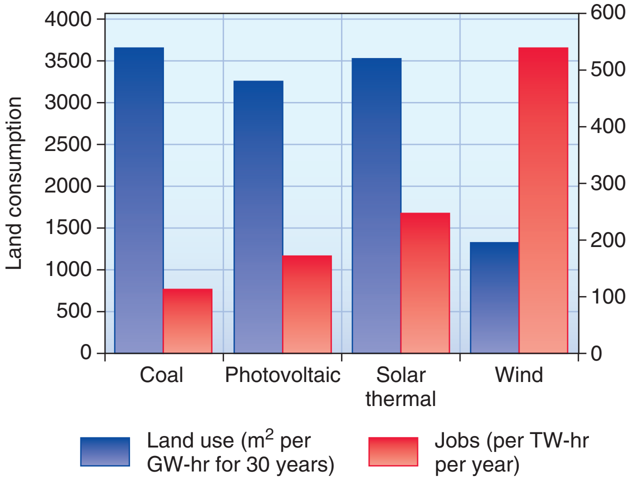
▲ **FIGURE 13.26** U.S. wind resource map. Mountain ranges and areas of the High Plains have the highest wind potential, but much of the country has fair to good wind supply. SOURCE: Data from U.S. Department of Energy.

towers up to 150 m tall with 62 m long blades that reach as high as a 45-story building. Each can generate 5 MW of electricity, or enough for 2,500 typical American homes. Out of commission for maintenance only about three days per year, many turbines can produce power 90 percent of the time. Theoretically up to 60 percent efficient, modern windmills typically produce about 35 percent of peak capacity under field conditions.

Prices for wind power have fallen sharply in the past few years, and this is currently the cheapest source of new electrical generation, costing as little as 3 cents/kWh compared to 4 to 5 cents/kWh for coal and five times that much for nuclear fuel. If the carbon "cap and trade" program proposed by President Obama becomes law, wind energy could be cheaper than fossil fuels in many places.

Like many countries, the United States has a tremendous potential for wind power. Large areas of the Great Plains and mountain states have persistent winds suitable for commercial development (fig. 13.26). Thirty-seven states now have utility-scale wind farms. Texas, with 10,377 MW, leads the nation, followed by Iowa, California, Illinois, and Minnesota, but there is a huge potential waiting to be tapped.

As figure 13.27 shows, wind power takes about one-third as much area and creates about five times as many jobs to create the same amount of electrical energy as coal when the land consumed by mining is taken into account. Furthermore, with each tower taking only about a 0.1 ha (0.25 acre) of cropland, farmers can continue to cultivate 90 percent of their land while getting $2,000 or more in annual rent for each wind machine. An even better return results if the landowner builds and operates the wind generator, selling the electricity to the local utility. Annual profits can be as much as $100,000 per turbine, a wonderful bonus for use of 10 percent of your land.



▲ **FIGURE 13.27** If you include the land required for mining, wind power takes about one-third as much area and creates about five times as many jobs to create the same amount of electrical energy as coal.

Cooperatives are springing up to help landowners and communities finance, build, and operate their own wind generators. One thousand megawatts of wind power (equivalent to one large nuclear or fossil fuel plant) can create more than 3,000 permanent jobs, while paying about $4 million in rent to landowners and $3.6 million in tax payments to local governments. About 20 Native American tribes, for example, have formed a coalition to study wind power. Together their reservations (which are in the windiest, least productive parts of the Great Plains) could generate at least 350,000 MW of electrical power, equivalent to about half of the current total U.S. installed electrical capacity.

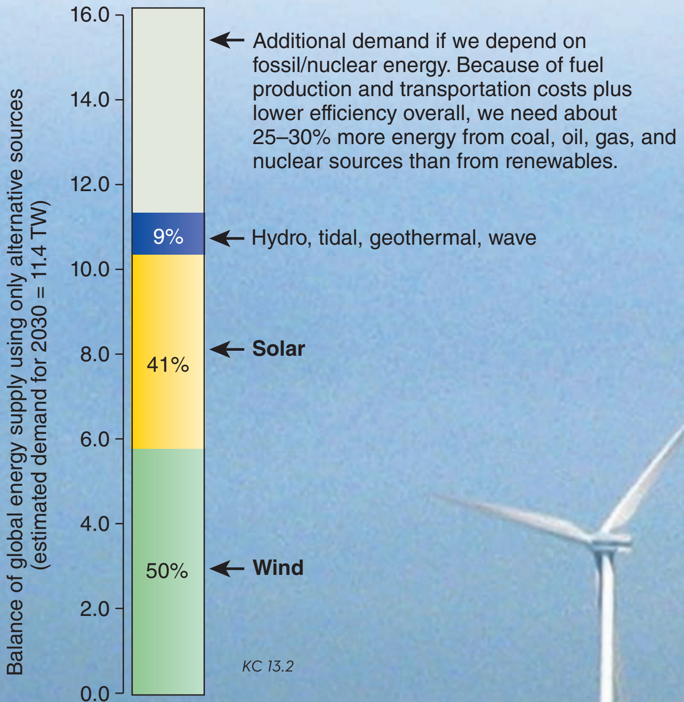
Wind does have limitations, however. Like solar energy, it's an intermittent source. Not every place has strong enough or steady enough wind to make this an economical resource. As the opening case study for this chapter shows, part of Europe's renewable energy plan is a network of offshore wind farms. Although the United States does have good offshore wind potential, installation and operating costs are much higher for ocean-based facilities, compared to those based on land.

There are problems with wind energy. In some places, high bird and bat mortality has been reported around wind farms. This seems to be particularly true in California, where rows of generators were placed at the summit of mountain passes where wind velocities are high but where migrating birds and bats are likely to fly into rotating blades. New generator designs and more careful tower placement seems to have reduced this problem in most areas. Although national polls in the United States show that 82 percent of the public supports additional wind power, the rate of support is often considerably less among people who live close to the towers.

Some people object to the sight of large machines looming over the landscape, and there are claims that low-frequency sound waves and flickering shadows produced by moving blades cause headaches, insomnia, digestive problems, panic attacks, and other health issues. There is no medical evidence to connect these symptoms to wind turbines, however, and researchers point out

How realistic is alternative energy?

It's very realistic, according to studies from Stanford University and the University of California at Davis.* With existing technology, renewable sources could provide all the energy we need, including the fossil fuels we use now. And we could save money at the same time. **Land-based wind, water power, and solar potential exceed all global energy consumption.** Renewable energy supplies over the oceans are even larger, since oceans cover two-thirds of the earth's surface. Many studies suggest that renewables could meet future demand more economically and more safely than fossil-based energy plans. How would this energy future look?



KC 13.2

GLOBAL ENERGY DEMAND, 2030
in terawatts (TW)
(1 TW = 1,000,000,000,000 watts)

KC 13.1

1. **Wind** could supply 50 percent of our energy, according to this plan. It would take 3.8 million large wind turbines to supply electricity to the whole world. Isn't that an impossible task? Not necessarily: we build that many cars and trucks every year worldwide.

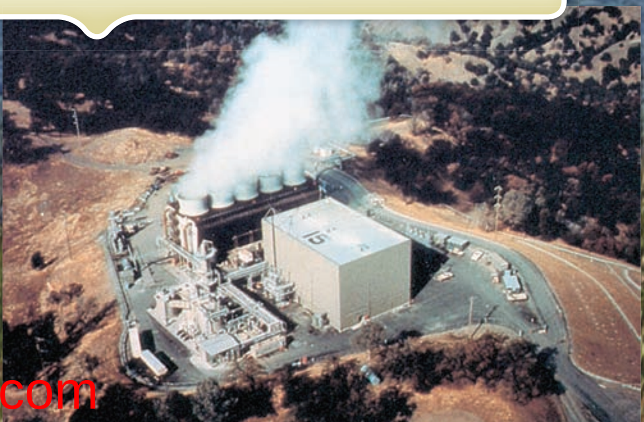
2. **Solar energy** could provide 41 percent of our total energy supply. It would take 1.7 billion rooftop photovoltaic systems and nearly 100,000 concentrated solar power plants to provide 4.6 TW. Rooftop collectors can be located where energy is used, so they don't lose energy in transmission and don't compete with other land uses.

KC 13.3

◀ Solar thermal collectors already are price competitive with fossil fuels, but they generally can't be located close to consumers, and they may require scarce cooling water in arid lands where sunshine is plentiful.

3. **Hydropower (dams, tidal, geothermal, wave energy)** could supply about 9 percent of our energy. Most major rivers are already dammed, but underwater turbines in rivers and tidal areas could be effective. Deep wells could tap geothermal energy, but there are worries about triggering earthquakes and contaminating aquifers.

KC 13.4



Geothermal plant ▶

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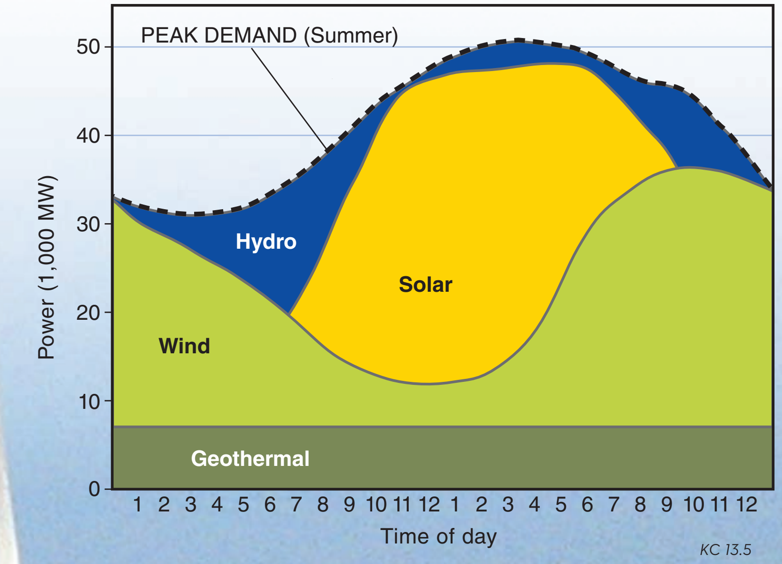
*For more information: see Jacobson, M. Z., and M. A. Delucchi. 2009. A path to sustainable energy. *Scientific American* 301(5) 58–65.

Wouldn't we have problems with unreliable supplies and a need for expensive storage?

Fortunately, the wind blows more at night to complement sunshine during the day. By balancing renewable sources, we can have just as reliable supplies as we now have with fossil fuels. Renewable sources also have a much better service record. Coal-burning power plants are out of production 46 days per year for maintenance. Solar panels and wind turbines average only 7 days down for repairs per year.

Solar, wind, and water power also solve two of our most pressing global problems: (1) the problem of climate change, perhaps the most serious and costly problem we face currently, as water shortages, crop failures, and refugee migrations destabilize developing regions; and (2) political conflict over fuel supplies, as in the oil fields of Iraq, Nigeria, and Ecuador, or nuclear fuel processing in Iran.



KC 13.5

In addition to the energy we can obtain from renewable sources, conservation measures could save up to half the energy we now use. Mass transit, weather-proofing, urban in-fill, and efficient appliances are among the available strategies that can save money in the near term and in the long term.

▲ Light Rail

KC 13.6

What would renewable energy cost?

By 2020, wind and hydroelectricity should cost about half as much as fossil fuels or nuclear power, and because renewable energy sources are inherently more efficient than fossil fuels, it should take about one-third less energy to supply the same services with sun, wind, and water.

CAN YOU EXPLAIN?

1. **What would be the greatest benefits of switching to renewable energy?**
2. **Which of these sources is forecast to produce the most energy?**
3. **How many windmills would we need in this plan?**
4. **Who would benefit most and least from an alternative energy future? From a fossil and nuclear future? Why?**

that such general complaints could be caused by a wide variety of sources. Furthermore, proponents say, the aesthetic or economic effects of windmills pale in comparison to the consequences of global climate change.

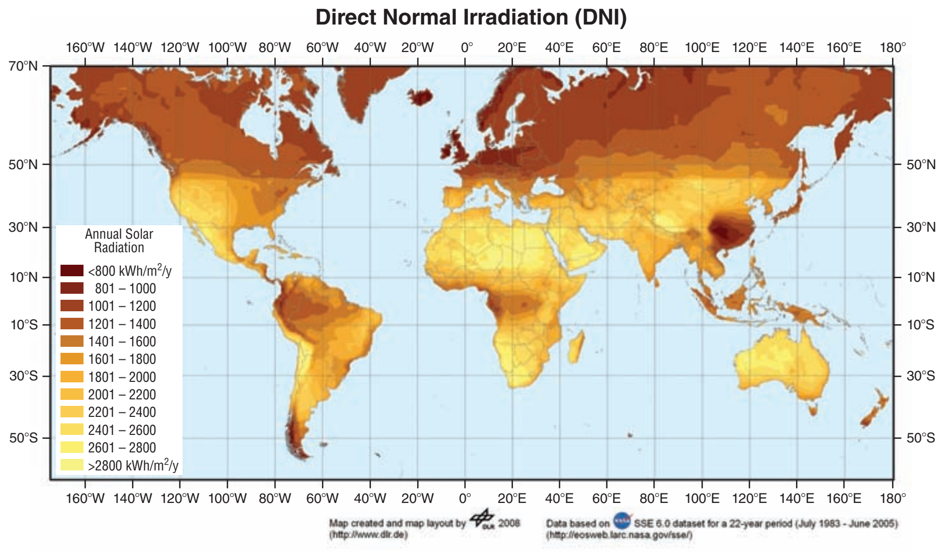
Solar energy is diffuse but abundant

The sun is a giant nuclear furnace in space, constantly bathing our planet with a free energy supply. Solar power drives winds and the hydrologic cycle. All biomass, as well as fossil fuels and our food (both of which are derived from biomass), results from conversion of light energy (photons) into chemical bond energy by photosynthetic bacteria, algae, and plants.

The average amount of solar energy arriving at the top of the atmosphere is 1,330 watts per square meter. About half of this energy is absorbed or reflected by the atmosphere (more at high latitudes than at the equator), but the amount reaching the earth's surface is still about 10,000 times all the commercial energy used each year. However, this tremendous infusion of energy comes in a form that, until recently, has been too diffuse and low in intensity to be used except for environmental heating and photosynthesis. But as the opening case study for this chapter shows, there are now ways to use this vast power source, so we might never again have to burn fossil fuels. Figure 13.28 shows world solar energy potential.

Solar collectors can be passive or active

Our simplest and oldest use of solar energy is passive heat absorption, using natural materials or absorptive structures with no moving parts to simply gather and hold heat. For thousands of years people have built thick-walled stone and adobe dwellings that slowly collect heat during the day and gradually release that heat at night. After cooling at night, these massive building materials maintain a comfortable daytime temperature within the house, even as they absorb external warmth.



▲ **FIGURE 13.28** Cumulative average annual solar radiation. Within 6 hours, deserts receive more energy from the sun than humans consume in a year. SOURCE: German Aerospace Center, 2008.

▲ **FIGURE 13.29** Solar water heaters can be scaled up to provide hot water and space heating for whole cities.

A modern adaptation of this principle is a glass-walled "sun space" or greenhouse on the south side of a building. Incorporating massive energy-storing materials, such as brick walls, stone floors, or barrels of heat-absorbing water, into buildings also collects heat to be released slowly at night. Active solar systems generally pump a heat-absorbing, fluid medium (air, water, or an antifreeze solution) through a relatively small collector, rather than passively collecting heat in a stationary medium like masonry. Active collectors can be located adjacent to or on top of buildings rather than being built into the structure. Because they are relatively small and structurally independent, active systems can be retrofitted to existing buildings.

A flat, black surface sealed with a double layer of glass makes a good solar collector. Water pumped through the collector picks up heat for space heating or to provide hot water. A collector with about 5 m^2 of surface can reach 95°C (200°F) and can provide enough hot water for an average family. China currently produces about 80 percent of the world's solar water heaters, which cost less than $200 each. At least 30 million Chinese homes get hot water and/or space heat from solar energy. In Europe, municipal solar systems provide district heating for whole cities (fig. 13.29).

In a symbolic act to illustrate his commitment to solar energy, Barack Obama restored to the White House roof the solar water heating panels that were removed 30 years ago by Ronald Reagan.

High-temperature solar energy

Solar high-temperature solar thermal plants are suitable for industrial-size facilities. The solar farms being built in North Africa for the Desertech project, for example, are **concentrating solar power** (CSP) systems. They use long, trough-shaped, parabolic mirrors to reflect and concentrate sunlight on a central tube containing a heat-absorbing fluid (see p. 302). Reaching much higher temperatures than possible in a basic flat panel collector, the fluid passes through a heat exchanger, where it generates steam to turn a turbine to produce electricity. Research by the German Aerospace Center suggests that CSP plants in North Africa and the Middle East should be able to provide 470,000 MW by 2050, or about 17 percent of the power used by the European Union. Costs, they estimate, should be equal to or lower than nuclear or fossil fuel power.

There are several advantages for a CSP plant besides fuel cost. Heat from the transfer fluid can be stored in a medium, such as molten salt, for later use. This allows the system to continue to generate electricity on cloudy days or at night. Desertech expects to be able to produce power nearly around the clock. In addition, those plants located near coastlines (see fig. 13.1) can use seawater to cool the power cycle (necessary to keep turbines operating). But the heat absorbed from turbines isn't all wasted. Much of it can be used to flash-evaporate water to create pure drinking water—something sorely lacking in most of North Africa and the Middle East. A 250 MW collector field is expected to provide 200 MW of electricity plus 100,000 m^3 (about 26 million gal) of distilled water per day.

But wouldn't highly polished mirrors in a CSP plant be damaged by desert sand storms? The parabolic troughs follow the sun to maximize solar energy absorption. On days when storms are forecast, the mirrors can be rotated into a protective position.

Solar-thermal power plants in California's Mojave Desert have been operating for over 20 years, and have withstood hailstorms, sandstorms, and gale-force winds. Wouldn't it take huge areas of land to capture solar energy? According to the German Aerospace Center, supplying 17 percent of Europe's energy requirements will take 2,500 km^2, or less than 0.3 percent of the Sahara desert. Interestingly, the nuclear disaster at Fukushima has made about 0.3 percent of Japan permanently uninhabitable. Which energy source do you think is a better choice?

CSP's relatively small footprint doesn't necessarily mollify critics, however. While some people regard deserts as useless, barren wastelands, others view them as beautiful, biologically rich, and captivating. In 2010, state regulators approved 13 large solar thermal facilities and wind farms for California's Mojave Desert. Subsequently, however, most of these projects were canceled or delayed by protests over land use. Some people argued that these plants would harm rare or endangered species, such as the desert tortoise or the fringe-toed lizard. Native American groups protested that some areas were sacred cultural sites, while others simply love the solitude and mystery of the desert and believe that large industrial facilities are an unwelcome intrusion. In response to this challenge, millions of hectares of desert have been added to new or existing protected areas to forestall energy development.

Another high-temperature system uses thousands of smaller mirrors arranged in concentric rings around a tall central tower (fig. 13.30). The mirrors, driven by electric motors, track the sun and focus light on a heat absorber at the top of the "power tower" where a transfer medium is heated to temperatures as high as 500°C (1,000°F), which then drives a steam-turbine electric generator. Under optimum conditions, a 50 ha (130 acre) mirror array should be able to generate 100 MW of clean, renewable power. Southern California Edison's Solar II plant in the Mojave Desert east of Los Angeles is an example. Its 2,000 mirrors focused on a 100 m (300 ft) tall tower generate 10 MW, or enough electricity for 5,000 homes at an operating cost far below that of nuclear power or oil.

▲ **FIGURE 13.30** A "Power Tower" is a form of concentrated solar thermal electrical generation. Thousands of movable mirrors focus intense energy on the tower, where fluid is heated to drive a steam turbine.

Because all the mirrors are focused on a single point, the heat transfer medium has to be capable of absorbing much higher energy levels than in solar troughs. So far most of these plants use liquid sodium or molten nitrate salt for heat absorption. These materials are much more corrosive and difficult to handle than the lower-temperature fluids suitable for a solar trough. The Worldwatch Institute estimates that U.S. deserts could provide more than 7,000 GW of solar energy—nearly seven times the potential in Europe.

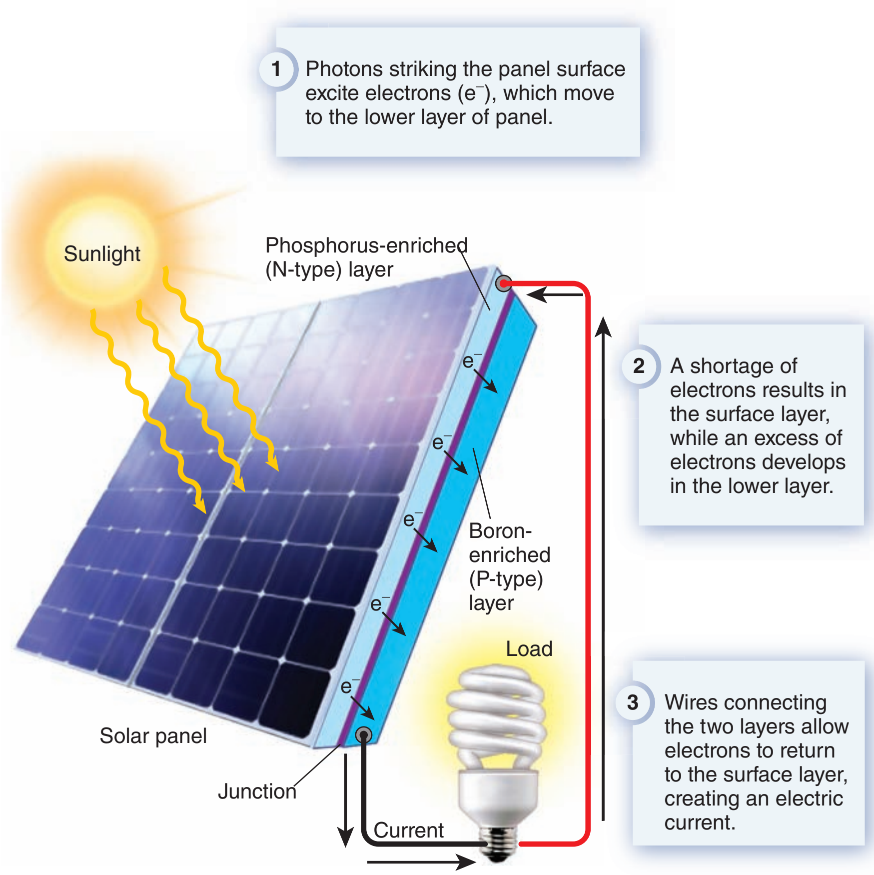
Photovoltaic cells generate electricity directly

Photovoltaic (PV) cells capture solar energy and convert it directly to electrical current by separating electrons from their parent atoms and accelerating them across a one-way electrostatic barrier formed by the junction between two different types of semiconductor material (fig. 13.31). The first photovoltaic cells were made by slicing thin wafers from giant crystals of extremely pure silicon.

Over the past 25 years, the efficiency of energy captured by photovoltaic cells has increased from less than 1 percent of incident light to more than 10 percent under field conditions and over 75 percent in the laboratory. Promising experiments are under way using exotic metal alloys, such as gallium arsenide, and semiconducting polymers of polyvinyl alcohol, which are more efficient in energy conversion than silicon crystals.

In 2010, thin-film photovoltaic cells finally broke the $1-per-watt barrier, a price that begins to make them competitive with fossil fuels and nuclear power in many situations. As further research improves their efficiency and lifespan, industry experts believe they could produce electricity for about 7¢ per kilowatt-hour by 2020 (see fig. 13.6). This makes photovoltaic solar competitive with fossil fuels in many places for utility-scale baseload power arrays (fig. 13.32a).

Systems that generate electricity closer to the end user, on the other hand, have many advantages. Mounting a photovoltaic system in your yard or on your rooftop delivers electricity without



▲ **FIGURE 13.31** When solar energy strikes a photovoltaic (PV) cell, an electron is dislodged from atoms in the p-layer in the silicon crystal. These electrons cross an electrostatic junction between different semiconductor materials. This creates a surplus of electrons in the n-layer and a shortage of electrons (or a positive charge) in the p-layer. The difference in charge creates an electric current in a circuit connecting the two layers.

the losses inherent in long-distance distribution. A photovoltaic array of about 30 to 40 m^2 will generate enough electricity for an efficient house.

One of the most promising developments in photovoltaic cell technology in recent years is the invention of **amorphous silicon collectors**. First described in 1968 by Stanford Ovshinky, these noncrystalline silicon semiconductors can be made into lightweight, paper-thin sheets that require much less material than conventional crystalline silicon cells. They also are cheaper to manufacture and can be made in a variety of shapes and sizes, permitting ingenious applications. Roof tiles with amorphous silicon collectors layered on their surface already are available (fig. 13.32b). Even flexible films can be coated with these materials.

There's a huge potential for rooftop solar energy. One study estimated that more than 1,000 mi^2 (2,590 km^2) of roofs suitable for photovoltaic systems in the United States could generate about three-quarters of present electrical consumption. In 2010, Southern California Edison started construction of photovoltaic arrays on roofs of warehouses and big-box retail stores (fig. 13.32c). Over the next five years, the utility expects to install a total of 250 MW of solar voltaic power. Overall, the 1 million solar roofs project aims to install 3,000 MW of photovoltaic energy on homes and apartments in California by 2016. More than \$2.8 billion in incentives are available to homeowners to cover costs.

Innovative financing programs are helping make this dream a reality. First introduced in Berkeley, California, **Property Assessed Clean Energy (PACE)** uses city bonds to pay for renewable energy and conservation expenses. The bonds are paid off through a 20-year assessment on property taxes. Decreased utility bills often offset tax increases, so that switching to renewable energy is relatively painless for the property owner. And after 20 years you own the system and never have to pay another electric bill.

(a) Base-load power facility

(b) Flexible, thin-film solar tiles

(c) Roof-top solar array

▲ **FIGURE 13.32** Solar photovoltaic energy is highly versatile and can be used in a variety of dispersed settings. (a) Utility-scale PV arrays can provide base-load power. (b) Thin-film PV collectors can be printed on flexible backing and used like oridinary roof tiles. (c) Millions of square meters of roof tops on schools and commercial buildings could be fitted with solar panels.

Some other financing arrangements that help overcome the high up-front costs of renewable energy are power purchasing agreements and solar leasing programs. In both cases an investor builds a certain amount of solar or wind energy in return for a contract to buy the energy produced at a specific rate for a fixed length of time. This frees property owners from large capital expenses, while giving investors a secure return on their investment. Feed-in tariffs that require utilities to buy excess power from homeowners at a fair price also help make solar photovoltaics economically feasible.

An intriguing option for storing electricity is in plug-in hybrid vehicles, which could provide an enormous, distributed battery array. You'd recharge your auto battery at night when power plants have excess generating capacity. During the day, your car would be plugged into a smart meter that could sell electricity back to your utility if prices rise. A few million mobile battery arrays could greatly help smooth out power peaks and valleys.

▲ **FIGURE 13.33** Hydropower dams produce clean, renewable energy but can be socially and ecologically damaging. China's Three Gorges Dam, shown here under construction, displaced 1.5 million people.

13.7 HYDROPOWER

Moving water is one of our oldest power sources. In early American settlements, water-powered gristmills and sawmills were essential, and most early industrial cities were built where falling water could run mills. The invention of water turbines in the nineteenth century greatly increased the efficiency of electricity-producing **hydropower dams**. By 1925 falling water generated 40 percent of the world's electric power. Since then, hydroelectric production capacity has grown 15-fold, but fossil fuel use has risen so rapidly that water power is now only one-quarter of total electrical generation. Still, many countries produce most of their electricity from falling water. Norway, for instance, depends on hydropower for 99 percent of its electricity; Brazil, New Zealand, and Switzerland all produce at least three-quarters of their electricity with water power. Canada is the world's leading producer of hydroelectricity, running 400 power stations with a combined capacity exceeding 60,000 MW. First Nations people protest, however, that their rivers are being diverted and lands flooded to generate electricity, most of which is sold to the United States.

The total world potential for hydropower is estimated to be about 3 million MW. If all of this capacity were put to use, the available water supply could provide between 8 and 10 terawatt hours (10^{12} watt-hours) of electrical energy. Currently we use only about 10 percent of the potential hydropower supply. The energy derived from this source in 1994 was equivalent to about 500 million tons of oil, or 8 percent of the total world commercial energy consumption.

Most hydropower comes from large dams

Much of the hydropower development since the 1930s has focused on enormous dams. There is a certain efficiency of scale in giant dams, and they bring pride and prestige to the countries that build them, but they can have unwanted social and environmental effects that spark protests in many countries. China's Three Gorges Dam on the Yangtze River, for instance, spans 2.0 km (1.2 mi) and is 185 m (600 ft) tall (fig. 13.33). The reservoir it creates is 644 km (400 mi) long and has displaced more than 1 million people.

In warm, dry climates, large reservoirs often suffer enormous water losses. Lake Nasser, behind the Aswan High Dam in Egypt, loses 15 billion m^3 each year to evaporation and seepage. Unlined canals lose another 1.5 billion m^3. Together, these losses represent one-half of the Nile River flow, or enough water to irrigate 2 million ha of land. The silt trapped by the Aswan High Dam formerly fertilized farmland during seasonal flooding and provided nutrients that supported a rich fishery in the delta region. Farmers now must buy expensive chemical fertilizers, and the fish catch has dropped almost to zero. Schistosomiasis, spread by snails that flourish in the reservoir, is an increasingly serious problem.

Large dams also destroy biodiversity. In 2010, Brazil announced approval of a controversial Belo Monte Dam on the Xingu River (a major tributary of the Amazon) in Para State. The $17 billion dam would be the third largest in the world. It will fuel development in this remote area, but it will flood 250 km^2 (96.5 mi^2) of tropical rainforest. Indigenous Kayapo people protested the loss of traditional hunting lands.

Dam promoters claim that the area to be flooded is less than the 5,000 km^2 originally planned, and equal to the forest flooded every year during the rainy season. Dam opponents, on the other hand, point out that the seasonally flooded forest is a unique ecosystem in which plants and animals are exquisitely adapted to changing water levels. The reservoir created by the dam will irreversibly change local ecology and eliminate many endemic species. Furthermore, decaying vegetation in the drowned forest will emit methane that could cause more global climate change than burning an equivalent amount of coal.

Unconventional hydropower comes from tides and waves

Ocean tides and waves also contain enormous amounts of energy that can be harnessed to do useful work. A **tidal station** works like a hydropower dam, with its turbines spinning as the tide flows through them. A high-tide/low-tide differential of several meters is required to spin the turbines. Unfortunately, variable tidal periods often cause problems in integrating this energy source into the electric utility grid. Nevertheless, some of these plants have operated for many decades.

Ocean wave energy can easily be seen and felt on any seashore. The energy that waves expend as millions of tons of water are picked up and hurled against the land, over and over, day after day, can far exceed the combined energy budget for both insolation (solar energy) and wind power in localized areas. Captured and turned into useful forms, that energy could make a substantial contribution to meeting local energy needs.

Dutch researchers estimate that 20,000 km of ocean coastline are suitable for harnessing wave power. Among the best places in the world for doing this are the west coasts of Scotland, Canada, the United States (including Hawaii), South Africa, and Australia. Wave energy specialists rate these areas at 40 to 70 kW per meter of shoreline. Altogether, it's calculated, if the technologies being studied today become widely used, wave power could amount to as much as 16 percent of the world's current electrical output.

Some of the **wave power** designs being explored include oscillating water columns that push or pull air through a turbine, as well as a variety of floating buoys, barges, and cylinders that bob up and down as waves pass, using a generator to convert mechanical motion into electricity. However, it's difficult to design a mechanism that can survive the worst storms.

An interesting new development in this field is the Pelamis generator developed by the Scottish company Ocean Power Delivery (fig. 13.34). The first application of this technology is now in operation 5 km off the coast of Portugal, with three units producing 2.25 MW of electricity, or enough to supply 1,500 Portuguese households. Another 28 units are currently being installed. Each of the units consists of four cylindrical steel sections linked by hinged joints. Anchored to the seafloor at its nose, the snakelike machine points into the waves and undulates up and down and side to side as swells move along its 125 m length. This motion pumps fluid to hydraulic motors that drive electrical generators to produce electricity, which is carried to shore by underwater cables. Portugal considers wave energy one of its most promising sources of renewable energy.

▲ **FIGURE 13.34** The Pelamis wave converter (named after a sea snake) is a 125 m long and 3.5 m diameter tube, hinged so it undulates as ocean swells pass along it. This motion drives pistons that turn electrical generators. Energy experts calculate that capturing just 1 to 2 percent of global wave power could supply at least 16 percent of the world's electrical demand.

Pelamis's inventor, Richard Yemm, says that survivability is the most important feature of a wave-power device. Being offshore, the Pelamis isn't exposed to the pounding breakers that destroy shore-based wave-power devices. If waves get too steep, the Pelamis simply dives under them, much as a surfer dives under a breaker. These wave converters lie flat in the water and are positioned far offshore, so they are unlikely to stir up as much opposition as do the tall towers of wind generators.

Geothermal heat could supply substantial amounts of energy

The earth's internal temperature can provide a useful source of energy in some places. High-pressure, high-temperature steam fields exist below the earth's surface. Around the edges of continental plates or where the earth's crust overlays magma (molten rock) pools close to the surface, this **geothermal energy** is expressed in the form of hot springs, geysers, and fumaroles. Yellowstone National Park is the largest geothermal region in the United States. Iceland, Japan, and New Zealand also have high concentrations of geothermal springs and vents.

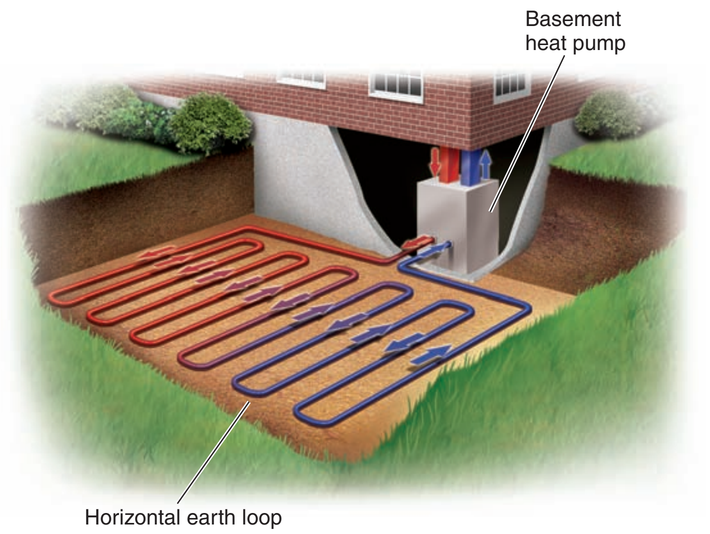
Depending on the shape, heat content, and access to groundwater, these sources produce wet steam, dry steam, or hot water. Iceland, which sits on a mid-ocean ridge (chapter 12), has abundant geothermal energy. Iceland has ambitious plans to be the first carbon-neutral country, largely because the earth's heat provides steam for heat and electric energy. Even places that don't naturally have geysers or hot springs may have hot spots close enough to the surface to be tapped by deep wells. In 2010, however, two large deep-well projects in Switzerland and California were shut down abruptly when evidence surfaced that they might trigger earthquakes.

Although few places have geothermal steam, the earth's warmth can help reduce energy costs nearly everywhere. Pumping water through deeply buried pipes can extract enough heat so that a heat pump will operate more efficiently. Similarly, the relatively uniform temperature of the ground can be used to augment air conditioning in the summer (fig. 13.35).

13.8 FUEL CELLS

Rather than store and transport energy, another alternative is to generate it locally, on demand. **Fuel cells** are devices that use ongoing electrochemical reactions to produce an electrical current. They are very similar to batteries except that, rather than recharging them with an electrical current, you add more fuel for the chemical reaction. Depending on the environmental costs of input fuels, fuel cells can be a clean energy source for office buildings, hospitals, or even homes.

All fuel cells consist of a positive electrode (the cathode) and a negative electrode (the anode) separated by an electrolyte, a material that allows the passage of charged atoms, called ions but is impermeable to electrons (fig. 13.36). In the most common

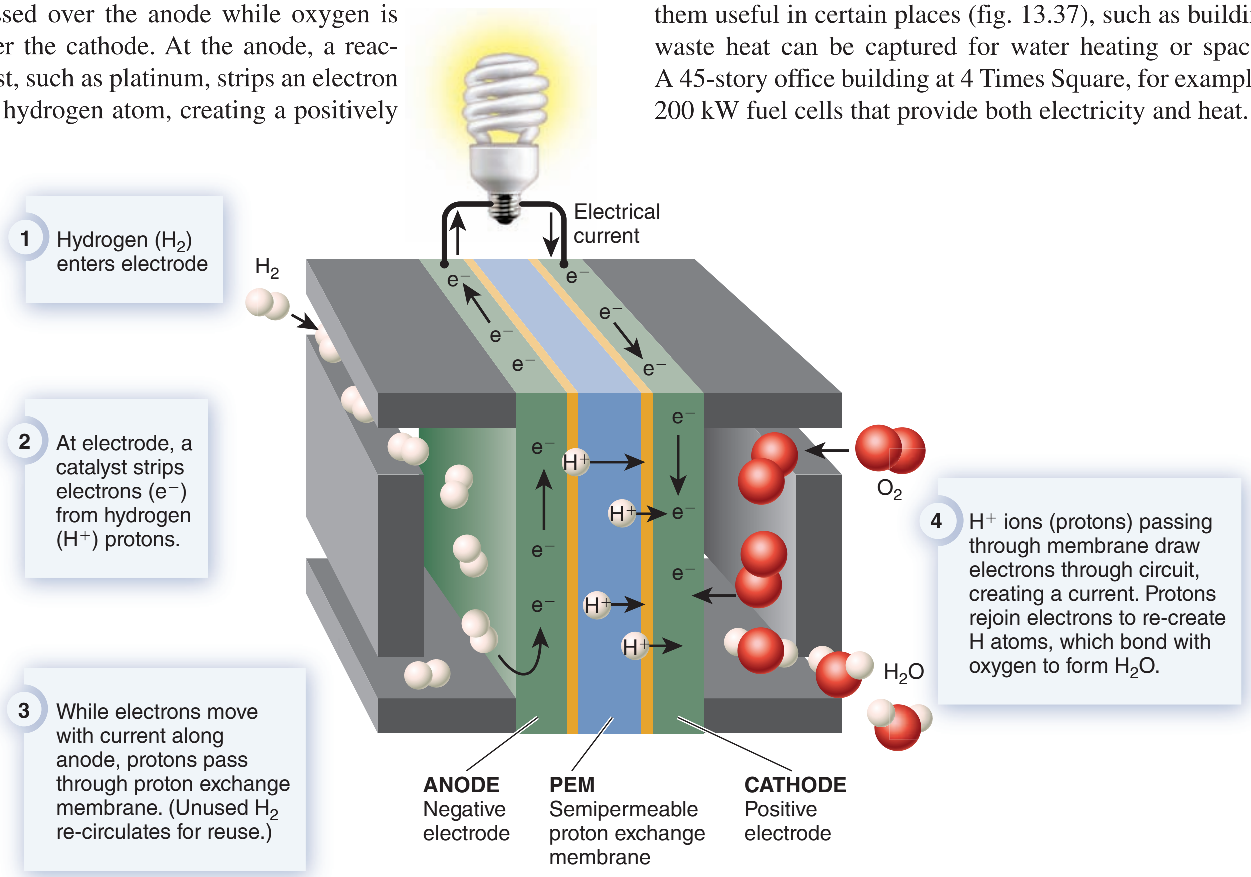


▲ **FIGURE 13.35** Geothermal energy can cut heating and cooling costs by half in many areas. In summer (shown here), warm water is pumped through buried tubing (earth loops), where it is cooled by constant underground temperatures. In winter, the system reverses and the relativity warm soil helps the house.

systems, hydrogen or a hydrogen-containing fuel is passed over the anode while oxygen is passed over the cathode. At the anode, a reactive catalyst, such as platinum, strips an electron from each hydrogen atom, creating a positively charged hydrogen ion (a proton). The hydrogen ion can migrate through the electrolyte to the cathode, but the electron is excluded. Electrons flow through an external circuit, and the electrical current generated by their passage can be used to do useful work. At the cathode, the electrons and protons are reunited and combined with oxygen to make water.

Fuel cells provide direct-current electricity as long as they are supplied with hydrogen and oxygen. For most uses, oxygen is provided by ambient air. Hydrogen can be supplied as a pure gas, but storing hydrogen gas is difficult and dangerous because it's highly explosive. An alternative is a device called a **reformer** or converter that strips hydrogen from fuels such as natural gas, methanol, ammonia, gasoline, ethanol, or even vegetable oil. Even methane effluents from landfills and wastewater treatment plants can be used as a fuel source. Or hydrogen gas could be provided by solar, wind, or geothermal facilities that generate electricity to hydrolyze (split) water.

A fuel cell that runs on pure oxygen and hydrogen produces no waste products except drinkable water and radiant heat. Other fuels create some pollutants (most commonly carbon dioxide), but the levels are typically far less than conventional fossil fuel combustion in a power plant or an automobile engine. Although the theoretical efficiency of electrical generation of a fuel cell can be as high as 70 percent, the actual yield is closer to 40 or 45 percent. The quiet, clean operation and variable size of fuel cells make them useful in certain places (fig. 13.37), such as buildings where waste heat can be captured for water heating or space heating. A 45-story office building at 4 Times Square, for example, has two 200 kW fuel cells that provide both electricity and heat. The same



▲ **FIGURE 13.36** Fuel cell operation. Electrons are removed from hydrogen atoms at the anode to produce hydrogen ions (protons) that migrate through a semipermeable electrolyte medium to the cathode, where they reunite with electrons from an external circuit and oxygen atoms to make water. Electrons flowing through the circuit connecting the electrodes create useful electrical current.

FIGURE 13.37 The Long Island Power Authority has installed 75 stationary fuel cells to provide reliable backup power.

building has photovoltaic panels on its façade, natural lighting, fresh-air intakes to reduce air conditioning, and a number of other energy conservation features.

Utilities are promoting renewable energy

Utility restructuring currently being planned in the United States could include policies to encourage conservation and alternative energy sources. Among the proposed policies are (1) "distributional surcharges" in which a small per kilowatt-hour charge is levied on all utility customers to help finance renewable energy research and development, (2) "renewables portfolio" standards to require power suppliers to obtain a minimum percentage of their energy from sustainable sources, and (3) **green pricing** that allows utilities to profit from conservation programs and charge premium prices for energy from renewable sources.

Some states already are pursuing these policies. For example, Iowa has a Revolving Loan Fund supported by a surcharge on investor-owned gas and electric utilities. This fund provides low-interest loans for renewable energy and conservation. Several states have initiated green pricing programs as a way to encourage a transition to sustainable energy. One of the first was in Colorado, where 1,000 customers agreed to pay $2.50 per month above their regular electric rates to help finance a 10 MW wind farm on the Colorado–Wyoming border. Buying a 100 kW "block" of wind power provides the same environmental benefits as planting a half acre of trees or not driving an automobile 4,000 km (2,500 mi) per year.

We need a supergrid

As you've seen in this chapter, many of the places with the greatest potential for both solar and wind development are far from the urban centers where power is needed. This means we'll need a vastly increased network of power lines if we're going to depend on wind or solar for a much greater proportion of our energy (fig. 13.38). In introducing his plans to double the amount of renewable energy over the next three years, President Obama said, "Today, the electricity we use is carried along a grid of lines and wires that dates back to Thomas Edison—a grid that can't support the demands of clean energy." He designated $4.5 billion to modernize and expand the transmission grid as part of the $86 billion in clean-energy investments in the economic recovery bill.

Fortunately, as we've seen in the case study for this chapter, high-voltage direct-current lines make it possible to transmit electricity over long distances with relatively minor loses. Interestingly, studies in California show that integration of renewable resources can smooth out daily variations. The wind blows more strongly at night, and the sun shines (obviously) during the day. And because hydropower can start up quickly, it easily fills in gaps. Even though the wind doesn't blow every day in most locations, linking together wind farms even a few hundred kilometers apart can give a steadier electrical supply than does a single site. A supergrid, such as the one proposed for Desertech, could make our entire energy supply more robust, reliable, and sustainable.

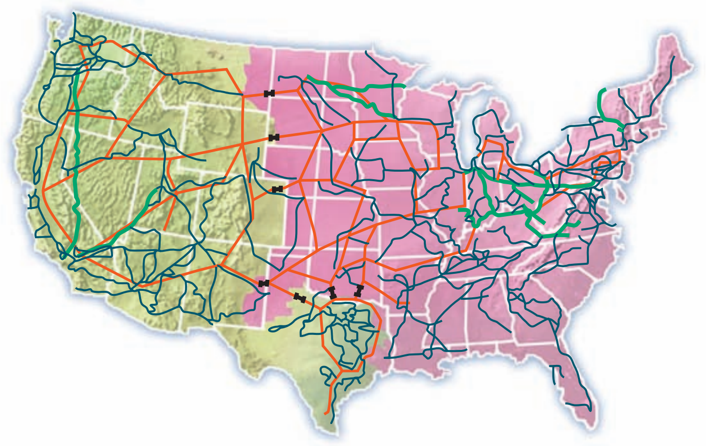


FIGURE 13.38 New high-voltage power lines (orange) will be needed to tie together regional networks (green) if the United States is to make effective use of its renewable energy potential. The pink area served by the Eastern electrical grid needs to be connected to the west by interlinks (black dots) for maximum efficiency.

13.9 WHAT'S OUR ENERGY FUTURE?

In 2008, former vice president Al Gore issued a bold and inspiring challenge to the United States. Currently, he said, "We're borrowing money from China to buy oil from the Persian Gulf to burn in ways that destroy the planet." He urged America to repower itself with 100 percent carbon-free electricity within a decade. Doing so, he proposed, would solve the three biggest crises we face—environmental, economic, and security—simultaneously. This ambitious project could create millions of jobs, spur economic development, and eliminate our addiction to imported fossil fuels.

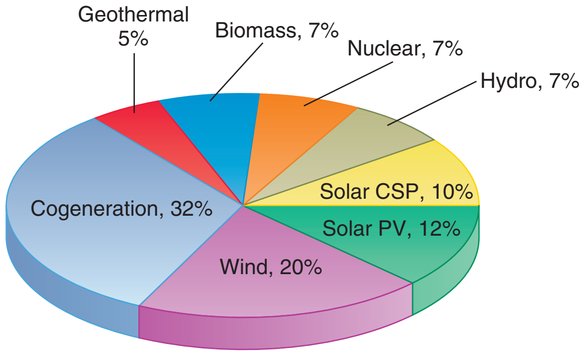
But could we get all our electricity from renewable, environmentally friendly sources in such a short time? Mark Jacobson from Stanford University and Mark Delucchi from the University of California–Davis believe we can. Moreover, they calculate that currently available wind, water, and solar technologies could supply 100 percent of the world's energy by 2030 and completely eliminate all our use of fossil fuels. They calculate that it would take 3.8 million large wind turbines (each rated at 5 MW), 1.7 billion rooftop photovoltaic systems, 720,000 wave converters, half a million tidal turbines, 89,000 concentrated solar power plants and industrial-sized photovoltaic arrays, 5,350 geothermal plants, and 900 hydroelectric plants, worldwide.

Wouldn't it be an overwhelming job to build and install all that technology? It would be a huge effort, but it's not impossible. Jacobson and Delucchi point out that society has achieved massive transformations before. In 1956 the United Sates began building the Interstate Highway System, which now extends 47,000 mi (75,600 km) and has changed commerce, landscapes, and society. And every year roughly 60 million new cars and trucks are added to the world's highways.

Is there enough clean energy to meet our needs? Yes, there is. In 2012, the U.S. National Renewable Energy Laboratory concluded that using currently available, affordable technology, renewable energy could supply 80 percent of total U.S. electricity generation in 2050, while meeting electricity demand on an hourly basis in every region of the country (fig 13.39). By the end of the twenty-first century, renewable sources could provide all our energy needs if we take the necessary steps to make this happen. After the meltdown of four nuclear reactors in Japan in 2011, Germany, Japan, Switzerland, Sweden, and several other countries announced intentions to move away from both nuclear and fossil fuels and to emphasize renewable energy sources in the future.

Interestingly, it would take about 30 percent less total energy to meet our needs with sun, wind, and water than to continue using fossil fuels. That's because electricity is a more efficient way to use energy than burning dead plants and animals. For example, only about 20 percent of the energy in gasoline is used to move a vehicle (the rest is wasted as heat). An electric vehicle, on the other hand, uses about three-quarters of the energy in electricity for motion. Furthermore, much of the energy from renewable sources could often be produced closer to where it's used, so there are fewer losses in transmission and processing.

Won't it be expensive to install so much new technology? Yes it will be, but the costs of continuing our current dependence on fossil fuels would be much higher. It's estimated that investing $700 billion per year now in clean energy will avoid 20 times that much in a few decades from the damages of climate change.



▲ **FIGURE 13.39** A renewable energy scenario for 2050. Cogeneration would mostly burn natural gas to generate both electricity and space heating.
SOURCE: 2008 Worldwatch Report.

One of the biggest challenges in moving to clean energy is that the wind doesn't blow all the time and the sun doesn't always shine in a given location. But a smart balance of sources can even out shortages. We'll need a large investment in the electric transmission grid—including some high-voltage interchange lines—to tie together the areas with abundant sun and wind with the cities where most people live. A smart grid that transmits energy more efficiently and safely is a good investment in any case.

China is taking bold steps to develop and employ wind, hydro, and solar energy. Let's hope that other developing countries follow their lead. Even some richer countries may see the benefits of this path. A decade ago it wasn't clear that clean energy would be technically or economically feasible. Now that it is, we all need to work to make it politically feasible as well. The energy choices we make now will have profound effects in the future on our lives and our environment.

CONCLUSION

Fossil fuels—oil, coal, and natural gas—remain our dominant energy sources. Coal is extremely abundant, especially in North America, but extracting and burning coal have been major causes of environmental damage and air pollution. Oil (petroleum) currently provides most of our transportation energy, but we're running out of cheap, easily extracted oil. And burning oil also releases greenhouse gases. Natural gas is more abundant than oil and cleaner than coal, but fracking, the most common method for extracting natural gas, may release so much methane into the atmosphere (in addition to contaminating surface and ground water) that the fuel it produces is actually worse for global climate change than coal.

Nuclear power doesn't create CO_2 while operating, but mining, processing, and shipping fuel, together with perpetual storage of wastes, results in far more greenhouse gases than does wind energy. Furthermore, the danger of accidents and the problem of storing the highly dangerous wastes are expensive and unresolved problems.

Conservation is a key factor in a sustainable energy future. New designs in housing, office buildings, industrial production, and transportation can all save huge amounts of energy. Biofuels, including ethanol and oil (biodiesel), vary greatly in their net energy yield and environmental effects, but cellulosic feedstocks and algae may provide useful energy. Hydropower can be clean and reliable, but a focus on huge dams has led to many environmental and social problems. Rapid innovations in solar, wind, wave power, and other renewable energy sources now make it possible to get all our energy from clean technologies. The choices we make about our energy sources and uses will have profound effects on our environment and society.

PRACTICE QUIZ

1. What is Desertech, and how will it help Europe meet its energy needs?
2. Define *energy*, *power*, and *kilowatt-hour* (kWh).
3. What are the major sources of global commercial energy?
4. How does energy consumption in the United States compare to that in other countries?
5. Why don't we want to use all the coal in the ground?
6. Where is most liquid oil located? How long are supplies likely to last?
7. What are *tar sands* and *oil shales*? What are the environmental costs of their extraction?
8. How are nuclear wastes now being stored?
9. Explain active and passive solar energy.
10. How do photovoltaic cells work?

CRITICAL THINKING AND DISCUSSION

Apply the principles you have learned in this chapter to discuss these questions with other students.

1. If you were the energy czar of your state or country, where would you invest your budget? Why?
2. We have discussed a number of different energy sources and energy technologies in this chapter. Each has advantages and disadvantages. If you were an energy policy analyst, how would you compare such different problems as the risk of a nuclear accident versus air pollution effects from burning coal?
3. If your local utility company were going to build a new power plant in your community, what kind would you prefer? Why?
4. The nuclear industry is placing ads in popular magazines and newspapers, claiming that nuclear power is environmentally friendly because it doesn't contribute to the greenhouse effect. How do you respond to that claim?
5. How would you evaluate the debate about net energy loss or gain in biofuels? What questions would you ask the experts on each side of this question? What worldviews or hidden agendas do you think might be implicit in this argument?
6. It clearly will cost a lot of money to switch from fossil fuels to renewables. How would you respond to someone who says that future costs from climate change are no concern of theirs?

DATA ANALYSIS Personal Energy Use

For many college students, a car and a computer are essentials of life. Cars are also one of our most important single uses of energy, so differences in efficiency can greatly affect your energy consumption (and energy costs). This exercise asks you to modify an Excel spreadsheet in order to evaluate the impact of vehicle efficiency on energy use.

Suppose you were to buy a very efficient car, such as the Honda Insight, rather than a sport utility vehicle, such as a Ford Excursion. How much energy would that save, and how long could you run your computer with that energy? Go to Connect to find a spreadsheet that explores these questions, and to answer questions about personal energy use.

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TO ACCESS ADDITIONAL RESOURCES FOR THIS CHAPTER, PLEASE VISIT CONNECT AT www.mcgrawhillconnect.com.

You will find LearnSmart, an adaptive learning system, Google Earth™ exercises, additional Case Studies, Data Analysis exercises, and an interactive ebook.