FIGURE 20.15 A large battery array, together with inverters and regulators, store photovoltaic energy on the Manzanita Indian Reservation in California.

typical lead-acid battery array sufficient to store several days of electricity for an average home would cost about $5,000 and weigh 3 or 4 tons (fig. 20.15). Still, some communities are encouraging use of electric vehicles because they produce zero emissions.

Other types of batteries also have drawbacks. Metal-gas batteries, such as the zinc-chloride cell, use inexpensive materials and have relatively high-energy densities, but have shorter lives than other types. Sodium-sulfur batteries have considerable potential for large-scale storage. They store twice as much energy in half as much weight as lead-acid batteries. They require an operating temperature of about 300°C (572°F) and are expensive to manufacture. Alkali-metal batteries have a high storage capacity but are even more expensive. Lithium-ion batteries have very long lives and store more energy than other types, but are the most expensive of all. Recent advances in thin-film technology may hold promise for future energy storage but often require rare, toxic elements that are both costly and dangerous.

Another strategy is to store energy in a form that can be turned back into electricity when needed. Pumped-hydro storage involves pumping water to an elevated reservoir at times when excess electricity is available. The water is released to flow back down through turbine generators when extra energy is needed. Using a similar principle, pressurized air can be pumped into such reservoirs as natural caves, depleted oil and gas fields, abandoned mines, or special tanks. An Alabama power company currently uses off-peak electricity to pump air at night into a deep salt mine. By day, the air flows back to the surface through turbines, driving a generator that produces electricity. Cool night air is heated to 1,600°F by compression plus geothermal energy, increasing pressure and energy yield.

An even better way to use surplus electricity may be electrolytic decomposition of water to H_2 and O_2. These gases can be liquefied (like natural gas) at −252°C (−423°F), making them easier to store and ship than most forms of energy. They are highly explosive, however, and must be handled with great care. They can be burned in internal combustion engines, producing mechanical energy, or they can be used to power fuel cells, which produce more electrical energy. There is a concern that if hydrogen escapes, it could destroy stratospheric ozone.

Flywheels are the subject of current experimentation for energy storage. Massive, high-speed flywheels, spinning in a nearly friction-free environment, store large amounts of mechanical energy in a small area. This energy is convertible to electrical energy. It is difficult, however, to find materials strong enough to hold together reliably when spinning at high speed. Flywheels have a disconcerting tendency to fail explosively and unexpectedly, sending shrapnel flying in all directions. Still, this might represent a useful technology if these problems can be overcome.

20.4 Fuel Cells

Rather than store and transport energy, another alternative would be to generate it locally, on demand. **Fuel cells** are devices that use ongoing electrochemical reactions to produce an electric 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.

Fuel cells are not new; the basic concept was recognized in 1839 by William Grove, who was studying the electrolysis of water. He suggested that rather than use electricity to break apart water and produce hydrogen and oxygen gases, it should be possible to reverse the process by joining oxygen and hydrogen to produce water and electricity. The term "fuel cell" was coined in 1889 by Ludwig Mond and Charles Langer, who built the first practical device using a platinum catalyst to produce electricity from air and coal gas. The concept languished in obscurity until the 1950s when the U.S. National Aeronautics and Space Administration (NASA) was searching for a power source for spacecraft. Research funded by NASA eventually led to development of fuel cells that now provide both electricity and drinkable water on every space shuttle flight. The characteristics that make fuel cells ideal for space exploration—small size, high efficiency, low emissions, net water production, no moving parts, and high reliability—also make them attractive for a number of other applications.

All fuel cells have similar components

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

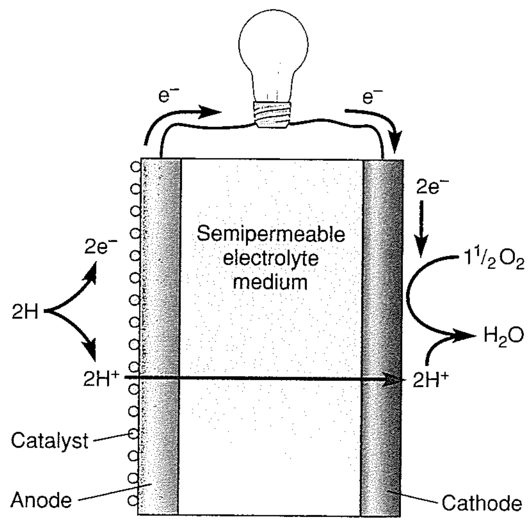

FIGURE 20.16 Fuel cell operation. Electrons are removed from hydrogen atoms at the anode to produce hydrogen ions (protons) that migrate through a semipermeable electrolyte medium to the cathode, where they reunite with electrons from an external circuit and oxygen atoms to make water. Electrons flowing through the circuit connecting the electrodes create useful electrical current.

impermeable to electrons (fig. 20.16). In the most common 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 pass 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.

The fuel cell provides direct-current electricity as long as it is 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 of its volume and explosive nature. Liquid hydrogen takes far less space than the gas, but must be kept below −250°C (−400°F), not a trivial task for most mobile applications. The 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. Many of these fuels can be derived from sustainable biomass crops. Even methane effluents from landfills and wastewater treatment plants can be used as a fuel source. Where a fuel cell can be hooked permanently to a gas line, hydrogen can be provided by solar, wind, or geothermal facilities that use electricity to hydrolyze water.

A fuel cell run on pure oxygen and hydrogen produces no waste products except drinkable water and radiant heat. When a reformer is coupled to the fuel cell, some pollutants are released (most commonly carbon dioxide), but the levels are typically far less than conventional fossil fuel combustion in a power plant or 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. This is about the same as an integrated gasification combined cycle (IGCC) plant (chapter 19). On the other hand, the quiet, clean operation and variable size of fuel cells make them useful in buildings where waste heat can be captured for water heating or space heating. A new 45-story office building at 4 Times Square, for example, has two 200-kilowatt fuel cells on its fourth floor that provide both electricity and heat. This same building has photovoltaic panels on its façade, natural lighting, fresh air intakes to reduce air conditioning, and a number of other energy conservation features.

U.S. automakers have focused most of their efforts to improve efficiency of fuel cells. While this would reduce pollution, eliminate our dependence on imported oil, and make a good use for wind or solar energy, critics claim that it will take 20 years or more to develop automotive fuel cells and build the necessary infrastructure. We should concentrate, instead, on hybrid engines, they say. Iceland, with no fossil fuels, but abundant geothermal energy, is determined to be the world's first hydrogen-based economy. They have one hydrogen filling station and a fleet of fuel cell buses.

The current from a fuel cell is proportional to the size (area) of the electrodes, while the voltage is limited to about 1.23 volts per cell. A number of cells can be stacked together until the desired power level is reached. A fuel cell stack that provides almost all of the electricity needed by a typical home (along with hot water and space heating) would be about the size of a refrigerator. A 200 kilowatt unit fills a medium-size room and provides enough energy for 20 houses or a small factory (fig. 20.17). Tiny fuel cells running on methanol may soon be used in cell phones, pagers, toys, computers, videocameras, and other appliances now run by batteries. Rather than buy new batteries or spend hours

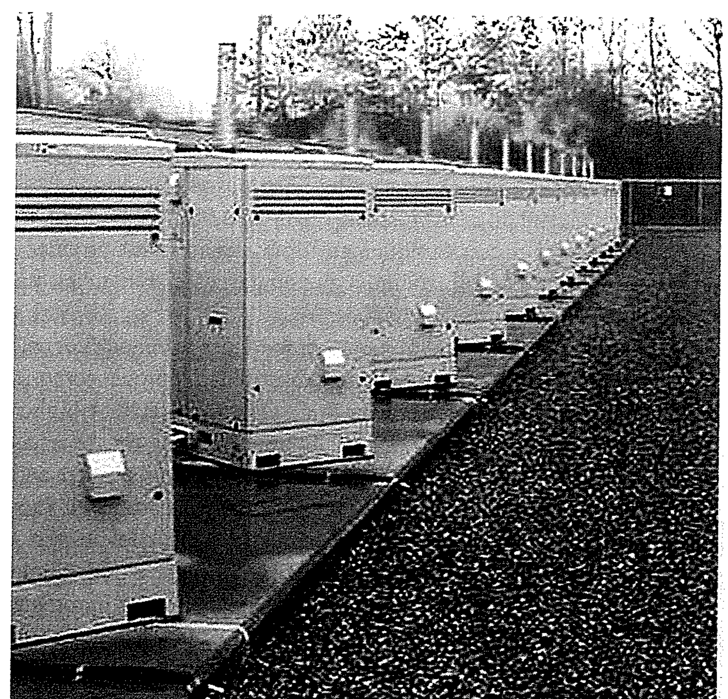

FIGURE 20.17 The Long Island Power Authority has installed 75 stationary fuel cells to provide reliable backup power.

TABLE 20.2

Fuel Cell Types

	Proton Electrolyte Membrane	Phosphoric Acid	Molten Carbonate	Solid Oxide
Electrolyte	Semipermeable organic polymer	Phosphoric acid	Liquid carbonate	Solid-oxide ceramic
Charge carrier	H^+	H^+	$CO_3^=$	$O^=$
Catalyst	Platinum	Platinum	Nickel	Perovskites (calcium titanate)
Operating temperature, °C	80	200	650	1,000
Cell material	Carbon or metal-based	Graphite-based	Stainless steel	Ceramic
Efficiency (percent)	Less than 40	40 to 50	50 to 60	More than 60
Heat cogeneration	None	Low	High	High
Status	Demonstration systems	Commercially available	Demonstration systems	Under development

Source: Alan C. Lloyd, 1999.

recharging spent ones, you might just add an eyedropper of methanol every few weeks to keep your gadgets operating.

Several different electrolytes can be used in fuel cells

Each fuel cell type has advantages and disadvantages (table 20.2). The design being developed for use in cars, buses, and trucks is called a proton exchange membrane (PEM). The membrane is a thin semipermeable layer of an organic polymer containing sulfonic acid groups that facilitate passage of hydrogen ions but block electrons and oxygen. The surface of the membrane is dusted with tiny particles of platinum catalyst. These cells have the advantage of being lightweight and operating at a relatively low temperature (80°C or 176°F). The fuel efficiency of PEM systems is typically less than 40 percent. Buses equipped with PEM stacks have been demonstrated in Chicago, Miami, and Vancouver, BC. DaimlerChrysler has a 5-passenger NECAR-4. Its 500 kg (1,100 lb) PEM stack costs $30,000 (compared to about $3,000 for a conventional gasoline engine) and produces performance comparable to most passenger cars, but takes up considerable interior room.

For stationary electrical generation, the most common fuel cell design uses phosphoric acid immobilized in a porous ceramic matrix as the electrolyte. Because this system operates at higher temperatures than PEM cells, less platinum is needed for the catalyst. It has a higher efficiency, 40 to 50 percent, but is heavier and larger than PEM cells. It also is less sensitive to carbon dioxide contamination than other designs. Hundreds of 200 kilovolt phosphoric acid fuel cells have been installed around the world. Some have run for decades. They supply dependable electricity in remote locations without the spikes and sags and risk of interruption common in utility grids. The largest fuel cell ever built was an 11 MW unit in Japan, that provides enough electricity for a small town.

A Central Park police station in New York City has a 200-kilowatt phosphoric acid fuel cell. The station is located in the middle of the park, so bringing in new electric lines would have cost $1.2 million and would have disrupted traffic and park use for months. A diesel generator was ruled out as too noisy and polluting. Solar photovoltaic panels were thought to be too obtrusive. A small, silent fuel cell provided just the right solution.

Carbonate fuel cells use an inexpensive nickel catalyst and operate at 650°C (1,200°F). The electrode is a very hot (thus the name molten carbonate) solution trapped in a porous ceramic. The charge carrier is carbonate ion, which is formed at the cathode where oxygen and carbon dioxide react in the presence of a nickel oxide catalyst. Migrating through the electrolyte, the carbonate ion reacts at the anode with hydrogen and carbon monoxide to release electrons. The high operating temperature of this design means that it can reform fuels internally and ionize hydrogen without expensive catalysts. Heat cogeneration is very good, but the high temperature makes these units more difficult to operate. It takes hours for carbonate fuel cells to get up to operating temperature, so they aren't suitable for short-term, quick-response uses.

The least developed fuel cell design is called solid oxide, because it uses a coated zirconium ceramic as an electrolyte. Oxygen ions formed by the titanium catalyst carry the charge across the electrolyte. Operating temperatures are 1,000°C (1,800°F). They have the highest fuel efficiency of any current design, but mass production of components has not yet been mastered, and these cells are still in the experimental stage.

20.5 Energy From Biomass

Photosynthetic organisms have been collecting and storing the sun's energy for more than 2 billion years. Plants capture about 0.1 percent of all solar energy that reaches the earth's surface. That kinetic energy is transformed, via photosynthesis, into chemical bonds in organic molecules (chapter 3). A little more than half of the energy that plants collect is spent in such metabolic activities as pumping water and ions, mechanical movement, maintenance of cells and tissues, and reproduction; the rest is stored in biomass.

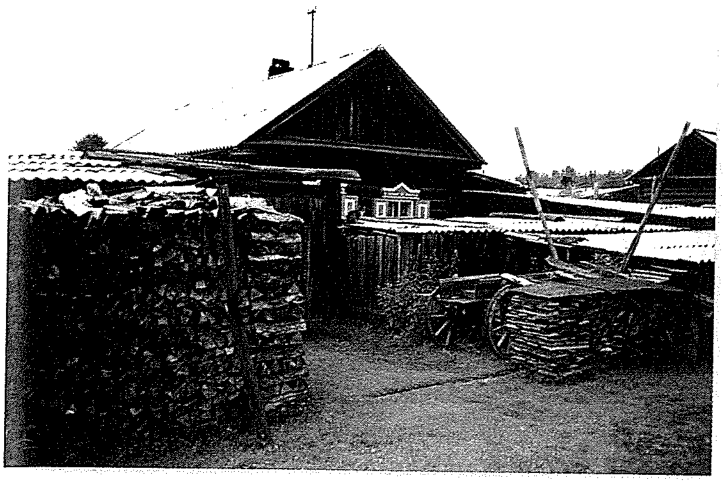

FIGURE 20.18 Firewood is an important resource in this Siberian village near Lake Baikal.

The magnitude of this resource is difficult to measure. Most experts estimate useful biomass production at 15 to 20 times the amount we currently get from all commercial energy sources. It would be ridiculous to consider consuming all green plants as fuel, but biomass has the potential to become a prime source of energy. It has many advantages over nuclear and fossil fuels because of its renewability and easy accessibility. Biomass resources used as fuel include wood, wood chips, bark, branches, leaves, starchy roots, and other plant and animal materials.

We can burn biomass

Wood fires have been a primary source of heating and cooking for thousands of years. As recently as 1850, wood supplied 90 percent of the fuel used in the United States. Wood now provides less than 1 percent of the energy in the United States, but in many of the poorer countries of the world, wood and other biomass fuels provide up to 95 percent of all energy used (fig. 20.18). The 1,500 million cubic meters of fuelwood collected in the world each year is about half of all wood harvested.

In northern industrialized countries, wood burning has increased since 1975 in an effort to avoid rising oil, coal, and gas prices. Most of these northern areas have adequate wood supplies to meet demands at current levels, but problems associated with wood burning may limit further expansion of this use. Inefficient and incomplete burning of wood in fireplaces and stoves produces smoke laden with fine ash and soot and hazardous amounts of carbon monoxide (CO) and hydrocarbons. In valleys where inversion layers trap air pollutants, the effluent from wood fires can present a major source of air quality degradation and health risk. Polycyclic aromatic compounds produced by burning are especially worrisome because they are carcinogenic (cancer-causing).

In Oregon's Willamette Valley or in the Colorado Rockies, where woodstoves are popular and topography concentrates contaminants, as much as 80 percent of air pollution on winter days is attributable to wood fires. Several resort towns, such as Vail, Aspen, and Telluride, Colorado, have banned installation of new woodstoves and fireplaces because of high pollution levels. Oregon, Colorado, and Vermont now have emission standards for new woodstoves. The Environmental Protection Agency ranks wood burners high on a list of health risks to the general population, and standards are being considered to regulate the use of woodstoves nationwide and to encourage homeowners to switch to low-emission models.

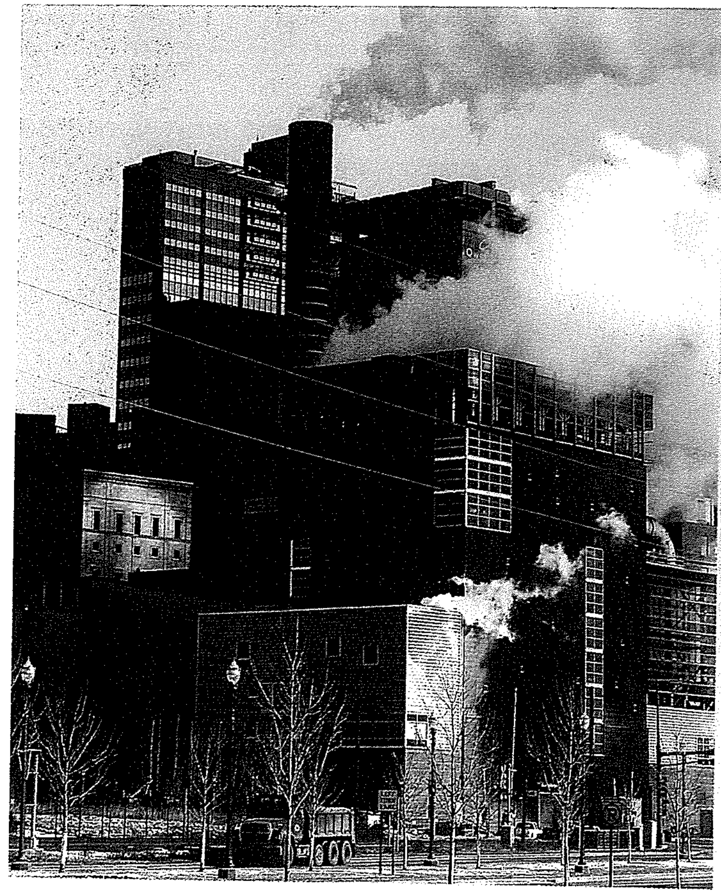

FIGURE 20.19 This district heating and cooling plant supplies steam heat, air conditioning, and electricity to three-quarters of downtown St. Paul, Minnesota, at about twice the efficiency of a remote power plant. It burns mainly urban tree trimmings and, thus, is carbon neutral.

Highly efficient and clean-burning woodstoves are available but expensive. Running exhaust gases through heat exchangers recaptures heat that would escape through the chimney, but if flue temperatures drop too low, flammable, tarlike creosote deposits can build up, increasing fire risk. A better approach is to design combustion chambers that use fuel efficiently, capturing heat without producing waste products. Brick-lined fireboxes with afterburner chambers to burn gaseous hydrocarbons do an excellent job. Catalytic combusters, similar to the catalytic converters on cars, also are placed inside stovepipes. They burn carbon monoxide and hydrocarbons to clean emissions and to recapture heat that otherwise would have escaped out the chimney in the chemical bonds of these molecules.

Wood chips, sawdust, wood residue, and other plant materials are being used in some places in the United States and Europe as a substitute for coal and oil in industrial boilers. St. Paul, Minnesota, for example has a district heating plant that supplies hot water to heat 25 million ft^2 of office and living space in 75 percent of all downtown buildings (fig. 20.19). This facility

FIGURE 20.20 A charcoal market in Ghana. Firewood and charcoal provide the main fuel for billions of people. Forest destruction results in wildlife extinction, erosion, and water loss.

burns 275,000 tons of wood per year (mostly from urban tree trimming) but has a flexible boiler that can burn a wide variety of fuels. It generates 25 MW of electricity and has a net efficiency of about 75 percent, or twice that of a typical coal-fired power plant.

Pollution-control equipment is easier to install and maintain in a central power plant like this than in individual home units.

Fuelwood is in short supply in many less-developed countries

Two billion people—about 40 percent of the total world population—depend on firewood and charcoal as their primary energy source. Of these people, three-quarters (1.5 billion) do not have an adequate, affordable supply. Most of these people are in the less-developed countries where they face a daily struggle to find enough fuel to warm their homes and cook their food. The problem is intensifying because rapidly growing populations in many developing countries create increasing demands for firewood and charcoal from a diminishing supply.

As firewood becomes increasingly scarce, women and children, who do most of the domestic labor in many cultures, spend more and more hours searching for fuel (fig. 20.20). In some places, it now takes eight hours, or more, just to walk to the nearest fuelwood supply and even longer to walk back with a load of sticks and branches that will only last a few days.

For people who live in cities, the opportunity to scavenge firewood is generally nonexistent and fuel must be bought from merchants. This can be ruinously expensive. In Addis Ababa, Ethiopia, 25 percent of household income is spent on wood for cooking fires. A circle of deforestation has spread more than 160 km (100 mi) around some major cities in India, and firewood costs up to ten times the price paid in smaller towns.

The poorest countries such as Ethiopia, Bhutan, Burundi, and Bangladesh depend on biomass for 90 percent of their energy. Often, the harvest is sustainable, consisting of deadwood, branches, trimmings, and shrubs. In Pakistan, for example, some 4.4 million tons of twigs and branches and 7.7 million tons of shrubs and crop residue are consumed as fuel each year with destruction of very few living trees.

In countries where fuel is scarce, however, desperate people often chop down anything that will burn. In Haiti, for instance, more than 90 percent of the once-forested land has been almost completely denuded and people cut down even valuable fruit trees to make charcoal they can sell in the marketplace. It is estimated that the 1,700 million tons of fuelwood now harvested each year globally is at least 500 million tons less than is needed. By 2025, if current trends continue, the worldwide demand for fuelwood is expected to be about twice current harvest rates while supplies will not have expanded much beyond current levels. Some places will be much worse than this average. In some African countries such as Mauritania, Rwanda, and the Sudan, firewood demand already is ten times the sustainable yield. Reforestation projects, agroforestry, community woodlots, and inexpensive, efficient, locally produced woodstoves could help alleviate expected fuelwood shortages in many places.

Dung and methane provide power

Where wood and other fuels are in short supply, people often dry and burn animal manure. This may seem like a logical use of waste biomass, but it can intensify food shortages in poorer countries. Not putting this manure back on the land as fertilizer reduces crop production and food supplies. In India, for example, where fuelwood supplies have been chronically short for many years, a limited manure supply must fertilize crops and provide household fuel. Cows in India produce more than 800 million tons of dung per year, more than half of which is dried and burned in cooking fires. If that dung were applied to fields as fertilizer, it could boost crop production of edible grains by 20 million tons per year, enough to feed about 40 million people.

When cow dung is burned in open fires, more than 90 percent of the potential heat and most of the nutrients are lost. Compare that to the efficiency of using dung to produce methane gas, an excellent fuel. In the 1950s, simple, cheap methane digesters were designed for villages and homes, but they were not widely used. Now, however, 6 million Chinese households use biogas for cooking and lighting. Two large municipal facilities in Nanyang will soon provide fuel for more than 20,000 families. Perhaps other countries will follow China's lead.

Methane gas is the main component of natural gas. It is produced by anaerobic decomposition (digestion by anaerobic bacteria) of any moist organic material. Many people are familiar with the fact that swamp gas is explosive. Swamps are simply large methane digesters, basins of wet plant and animal wastes sealed from the air by a layer of water. Under these conditions, organic materials are decomposed by anaerobic (oxygen-free) rather than aerobic (oxygen-using) bacteria, producing flammable gases instead of carbon dioxide. This same process may be reproduced artificially by placing organic wastes in a container and providing warmth and water

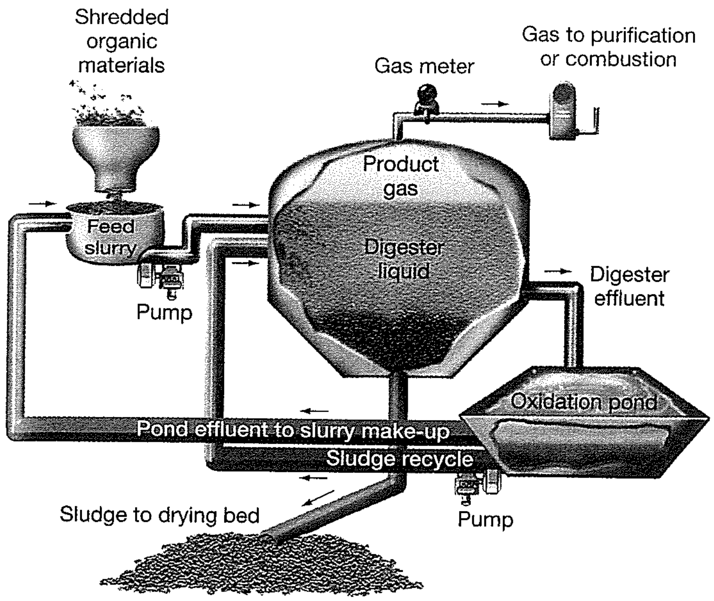

FIGURE 20.21 Continuous unit for converting organic material to methane by anaerobic fermentation. One kilogram of dry organic matter will produce 1–1.5 m^3 of methane, or 2,500–3,600 million calories per metric ton.

FIGURE 20.22 Harvesting marsh reeds (*Phragmites* sp.) in Sweden as a source of biomass fuel. In some places, biomass from wood chips, animal manure, food-processing wastes, peat, marsh plants, shrubs, and other kinds of organic material make a valuable contribution to energy supplies. Care must be taken, however, to avoid environmental damage in sensitive areas.

(fig. 20.21). Bacteria are ubiquitous enough to start the culture spontaneously.

Burning methane produced from manure provides more heat than burning the dung itself, and the sludge left over from bacterial digestion is a rich fertilizer, containing healthy bacteria as well as most of the nutrients originally in the dung. Whether the manure is of livestock or human origin, airtight digestion also eliminates some health hazards associated with direct use of dung, such as exposure to fecal pathogens and parasites.

How feasible is methane—from manure or from municipal sewage—as a fuel resource in developed countries? Methane is a clean fuel that burns efficiently. Any kind of organic waste material: livestock manure, kitchen and garden scraps, and even municipal garbage and sewage can be used to generate gas. In fact, municipal landfills are active sites of methane production, contributing as much as 20 percent of the annual output of methane to the atmosphere. This is a waste of a valuable resource and a threat to the environment because methane absorbs infrared radiation and contributes to the greenhouse effect (chapter 15). About 300 landfills in the United States currently burn methane and generate enough electricity together for a million homes. Another 600 landfills have been identified as potential sources for methane development. Hydrologists worry, however, that water will be pumped into landfills to stimulate fermentation, thus increasing the potential for groundwater contamination.

Cattle feedlots and chicken farms in the United States are a tremendous potential fuel source. Collectible crop residues and feedlot wastes each year contain 4.8 billion gigajoules (4.6 quadrillion BTUs) of energy, more than all the nation's farmers use. The Haubenschild farm in central Minnesota, for instance, uses manure from 850 Holsteins to generate all the power needed for their dairy operation and still have enough excess electricity for an additional 80 homes. In January 2001, the farm saved 35 tons of coal, 1,200 gallons of propane, and made $4,380 from electric sales.

Municipal sewage treatment plants also routinely use anaerobic digestion as a part of their treatment process, and many facilities collect the methane they produce and use it to generate heat or electricity for their operations. Although this technology is well-developed, its utilization could be much more widespread.

Biofuels could replace some oil-based energy

As the opening story of this chapter shows, biomass can make a substantial contribution to renewable energy supplies. The islands of Samsø and Ærø get about half their space heating from biomass, both from straw and other crop wastes and from energy crops, such as reeds and elephant grass growing on land unsuitable for crops (fig. 20.22). As we discussed earlier, burning these crops in a industrial boiler for district heating makes it easier to install and maintain pollution-control equipment than in individual stoves. Most plant material has low sulfur, so it doesn't contribute to acid rain. And because it burns at a lower temperature than coal, it doesn't create as much nitrogen oxides. Of course, these crops are carbon neutral—that is, they absorb as much CO_2 in growing as they emit when burned. Wood chips and straw make great fuel for a boiler, but what about fuel for vehicles? You don't want to drive around with a hay bale in the backseat.

Biofuels, ethanol or methanol made from plant materials, or diesel fuel made from vegetable oils or animal fat, could meet much of our transportation needs. Alcohols can be burned directly in engines adapted to use these fuels, or they can be mixed with gasoline to be used in any normal engine. Ethanol makes gasoline burn cleaner and most states now require that 5 to 10 percent of an oxygenated additive, such as ethanol, be added to gasoline. Most ethanol is now made from grain, but it can also be made from wood chips, straw, or any **cellulosic** material (composed largely of cellulose).

Ethanol could be a solution to grain surpluses and bring a higher price for farmers than the food market offers. As one Midwestern politician pointed out, "The WTO is putting pressure on Europe and America to reduce farm subsidies, but there's no rule that forbids subsidies for energy crops." There has been much debate about whether ethanol represents a net energy gain (Exploring Science p. 465). Modern state-of-the-art ethanol refineries claim at least a 35 percent gain in ethanol made from corn (maize) over the energy content of the inputs. Removing high-value nutraceuticals, such as L-ribose and levoglucoseon before fermentation makes ethanol production much more profitable. Ethanol currently can be made for about $1 per gal (3.8l) in the United States, and about half that amount in Brazil. Local residents sometimes complain, however, about odors from ethanol plants.

The United States already has about 5 million **flex-fuel vehicles** that can burn variable mixtures of ethanol and gasoline, but few of them currently use anything beyond the standard 5 or 10 percent ethanol blend. Owners either don't know that they could burn up to 85 percent ethanol or they don't have access to biofuel. Vehicle manufacturers continue to make these engines because a special clause in the U.S. Energy Bill allows them to sell more gas guzzlers if they also produce flex-fuel vehicles. The ironic effect is that the existence of these alternative fuel vehicles actually results in more oil consumption.

Brazil is the current world leader in crop-based ethanol production. In 2006, Brazil refined some 18 billion l (4.7 billion gal) of ethanol, mostly from sugarcane waste called bagasse). By 2012, Brazil expects to double this output and to be exporting billions of liters of biofuels to other countries. Almost all new vehicles in Brazil now have flex-fuel engines. Most motorists mix their own combination (about 80 percent ethanol is most common) right at the pump (fig. 20.23). They are motivated to do so, because ethanol is about 40 percent cheaper than gasoline. Rapidly increasing soy and corn production in Brazil (chapter 7) could also provide vegetable oils for diesel fuel. Brazil gets about three times as much ethanol from a ton of sugarcane than the U.S. gets from a ton of shelled corn.

Ethanol production is growing explosively in the United States. Currently 101 biorefineries are operating and 39 more are under construction. Some people think we may have too many of these factories. In 2006, the U.S. produced 17.4 billion l of ethanol (4.6 billion gal), mostly from shelled corn. Like Brazil, the U.S. hopes to double this yield by 2012. Most American states now require small amounts of ethanol to improve air quality. Some states mandate higher ethanol content as a way of reducing oil dependence and supporting farmers. The highest of these is in Minnesota which requires 20 percent ethanol in gasoline, the highest concentration considered feasible without modifying ordinary engines.

FIGURE 20.23 Alcohol, mostly from sugarcane waste, is cheaper than either gasoline or diesel fuel in Brazil. All passenger vehicles in Brazil are required to use at least 20 percent ethanol.

Should we use food for fuel?

Many Midwestern states see ethanol as a bonanza for farmers, but others doubt the wisdom of using food for fuel. Already, the 2 billion bushels of corn used per year for fuel production in the U.S. has increased prices by about 50 percent. This is great for farmers, but it has driven up the price of tortillas in Mexico (since NAFTA, the Mexican maize market has been dominated by the U.S.), a burden for poor people there. Most soy and corn grown in America are used for animal feed, so diverting a significant portion of the crop to fuel is driving up meat, milk, and egg prices. On the other hand, as much as 80 percent of the starting grain weight can be recovered as high-protein animal feed after fermentation, so ethanol production may not affect meat prices very much in the long run. Critics point out that even if we convert all our soy and corn crop to fuel, it would replace only about 12 percent of our current gasoline consumption. Increasing fuel economy standards by 12 percent would reduce oil consumption just as much, and would save taxpayers about $10 billion per year in ethanol subsidies.

Energy crops, such as switch grass, cattails, and hybrid poplar, could be grown specifically as an energy source on marginal

Exploring SCIENCE — Net Energy Balance of Biofuels

Biofuels (alcohol refined from plant material or diesel fuel made from vegetable oils or animal fats) are thought by many people to be the answer to both our farm crisis and our fuel needs. But do these crops represent a net energy gain? Or does it take more fossil fuel energy to grow, harvest, and process crop-based biofuels than you get back in the finished product? Some researchers calculate that crops can produce a net energy gain, while others insist that we can't even break even in converting biomass to fuel.

David Pimental from Cornell University, for example, is one of the most vocal critics of biofuels. He calculates that it takes 29 percent more energy to refine ethanol from corn than it yields. Soy-based biodiesel is equally inefficient, he maintains, and cellulose-based biofuels are even worse. Cellulosic crops take at least 50 percent more energy than they produce as ethanol, according to his calculations.

Among others who dispute these calculations are Bruce Dale of Michigan State University and John Sheehan from the U.S. National Renewable Energy Laboratory, who argue that biofuels produced by modern techniques represent a positive energy return. Dramatic improvements in farming productivity, they believe, coupled with much greater efficiency in ethanol fermentation now yield about 35 percent more energy in ethanol from corn than in the inputs, and cellulosic crops would be at least four times better.

A valuable addition to this debate comes from the work of ecologist David Tilman and his colleagues at the Cedar Creek Natural History Area in Minnesota. This group grew experimental plots containing 1, 2, 4, 8, or 16 perennial herbaceous grassland species on degraded farmland for ten years. Each of the 152 plots contained a random mixture and number of species. All plots were unfertilized and irrigated only during establishment. Aboveground biomass was collected every fall, from each plot. Energy yields were calculated from dry biomass. Using numbers from other sources, the authors calculate energy outputs from various fuel derivation methods.

The most diverse plots (16 species), which they call low-input high-diversity grassland mixtures (LIHD), had the highest biomass yields (68.1 GJ/ha/yr) in this experiment. The fossil fuel energy needed to grow, harvest, and transport this biomass to a biofuel production facility is calculated to be 4.0 GJ/ha/yr. If the biomass were burned directly in an electric generating station, Tilman calculates, it would yield about 22 GJ/ha/yr, or about 5.5 times as much energy as the inputs. Cellulosic ethanol production would have about the same net energy yield. Production of biomass synfuel in an integrated gasification combined cycle (IGCC) facility similar to that described in chapter 19 would have the best net energy ratio (8.1) of any biofuel. These polycultures of native species can be grown on marginal farmland, so they don't need to displace food crops. Another great advantage is that prairie plants store carbon in their roots. While monocultures didn't have a significant net carbon storage, the most diverse mixtures have a net carbon storage of 4.4 Mg/ha/yr. Thus, they take up more carbon than is released during fuel production.

Corn-based ethanol produces more fuel energy per hectare than do LIHD mixtures, but it also requires far higher inputs for crop and fuel production. Thus, the net energy ratio for corn-based ethanol is far lower than that for native prairie species.

Biomass Fuel Efficiency

Fuel	Inputs (GJ/ha)	Outputs (GJ/ha)	Net Energy Ratio
Corn ethanol	75.0	93.8	1.2
Soy ethanol	15.0	28.9	1.9
Cellulosic electricity	4.0	22.0	5.5
Cellulosic ethanol	4.0	21.8	5.4
Cellulosic synfuel	4.0	32.4	8.1

Source: Tilman, et al. 2006. *Science* 314:1598.

land (fig. 20.24). These perennial crops require less cultivation (and therefore result in less erosion) than annual row crops. They may also reduce fertilizer and pesticide use. In his study of biodiversity and productivity in native prairie species, ecologist David Tilman found that experimental plots with the highest diversity (16 species) accumulated more than twice as much aboveground biomass as single species plots. Furthermore, these high-diversity plots also store 160 percent more carbon in the soil than do single species. These native plants are adapted to low-nitrogen soil and dry conditions, so they don't need irrigation, fertilizer, or pesticides. Tilman calls these mixed polycultures of perennial native species **low-input high-diversity biofuels,** and suggests they could be a good way to use marginal land that isn't suitable for crop production.

Cellulosic ethanol has a much better net yield than corn or soy fermentation. In the laboratory, up to 8.1 units of energy are produced from cellulosic crops for every unit invested. The biggest problem with fermenting cellulosic crops is the insoluble lignin that holds cells together. It's hoped that bacteria can be engineered to solubilize the lignin. If it could be removed, it would be a valuable by-product. So far, there are no commercial-scale cellulosic ethanol plants in North America, but the Department of Energy announced grants in 2007 totaling $385 million for six biorefinery projects. These pilot plants will use a variety of feedstocks including rice and wheat straw, milo stubble, switchgrass, organic waste from landfills, corn cobs and stalks, and woody crops.

Water is another worry about the sustainability of biofuels. Currently, it takes 3 to 6 liters of water for each liter of ethanol

FIGURE 20.24 Some of these 3-year-old hybrid poplars are 6 m tall. If they continue to grow at this rate, and cellulosic ethanol production becomes cost-effective, they may make a good energy crop for marginal land.

produced. In many plains states where grain is grown, there isn't enough water for both agriculture and fuel production. In some areas, plans for new processing facilities are being scaled back because of water shortages. So, although biofuels could make a useful contribution to our fuel supplies, especially in the interim between the age of fossil fuels and whatever comes next, there are concerns about the social and environmental impacts of a sudden switch to these alternate energy sources.

Just about anything organic, from turkey entrails to cow dung or sugarcane waste can be used to make biodiesel, and with oil over $70 a barrel in recent years, just about everything is. Factories have been set up next to meat-processing plants to convert waste material into biodiesel. They work well, but aren't currently economical given U.S. policies that favor fossil fuels. These plants are much more profitable in Europe, where waste disposal and carbon emission limits are more strict. Many people are converting diesel engines to burn discarded restaurant deep frying fat. They say that these "greasel" engines leave a pleasant whiff of french fries or egg rolls as they roll along.

A much greater potential for diesel fuel is from vegetable oil, which can be burned in most diesel engines without any processing except filtering. The European Union currently consumes about 4 million metric tons (1 billion gal) of biodiesel fuel, mostly made from rapeseed oil (called canola oil in North America). Plans are to triple this production by 2012 to 10 percent of all fuel consumed in Europe. Planners expect this move to create 250,000 jobs, reduce oil imports, improve air quality, save consumers billions of Euros, and reduce CO_2 emissions by 200 million tons per year. Already, however, this increased use of vegetable oils has reduced the amount available for human consumption. Tropical countries, such as Indonesia and Malaysia, hope that biodiesel demand will stimulate palm oil exports which have fallen out of favor for human diets. Conservationists, however, worry that increasing oil palm plantations will lead to more tropical forest destruction.

20.6 Energy from the Earth's Forces

The winds, waves, tides, ocean thermal gradients, and geothermal areas are renewable energy sources. Although available only in selected locations, these sources could make valuable contributions to our total energy supply.

Falling water has been used as an energy source since ancient times

The invention of water turbines in the nineteenth century greatly increased the efficiency of 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 20 percent of total electrical generation. Still, many countries produce most of their electricity from falling water (fig. 20.25). Norway, for instance, depends on hydropower for 99 percent of its electricity. Currently, total world hydroelectric production is about 3,000 terrawatt hours (10^{12} Whr). Six countries, Canada, Brazil, the United States, China, Russia, and Norway, account for more than half that total. Approximately two-thirds of the economically feasible potential remains to be developed. Untapped hydro resources are still abundant in Latin America, Central Africa, India, and China.

Much of the hydropower development in recent years has been in enormous dams. There is a certain efficiency of scale in

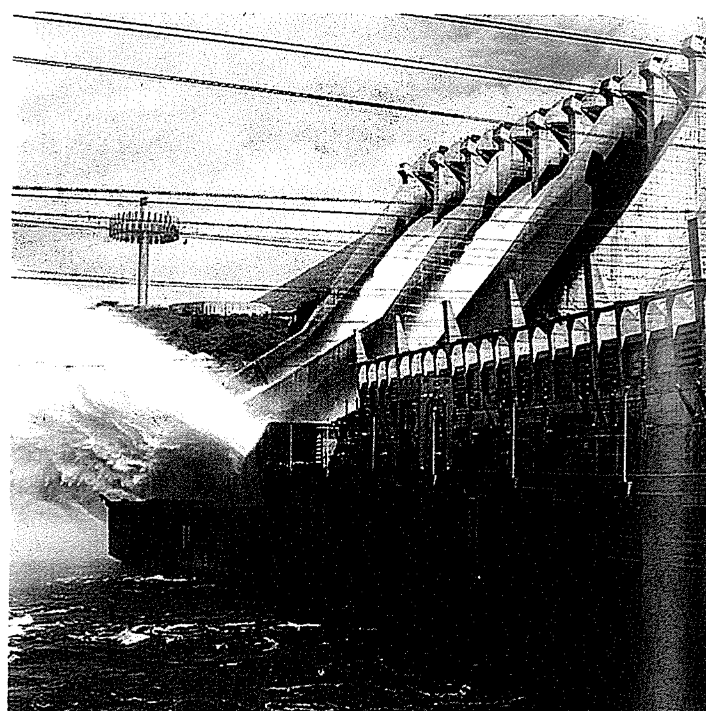

FIGURE 20.25 Hydropower dams produce clean renewable energy but can be socially and ecologically damaging.

giant dams, and they bring pride and prestige to the countries that build them, but, as we discussed in chapter 17, they can have unwanted social and environmental effects. The largest hydroelectric dam in the world at present is the Three Gorges Dam on China's Yangtze River, which spans 2 km and will be 185 m (600 ft) tall when completed in 2009. Designed to generate 25,000 MW of power, this dam should produce as much energy as 25 large nuclear power plants when completed. The lake that it is creating already has displaced at least 1.5 million people and submerged 5,000 archaeological sites.

There are other problems with big dams, besides human displacement, ecosystem destruction, and wildlife losses. Dam failure can cause catastrophic floods and thousands of deaths. Sedimentation often fills reservoirs rapidly and reduces the usefulness of the dam for either irrigation or hydropower. In China, the Sanmenxia Reservoir silted up in only two years, and the Laoying Reservoir filled with sediment before the dam was even finished.

Rotting vegetation in artificial impoundments can have disastrous effects on water quality. When Lake Brokopondo in Suriname flooded a large region of uncut rainforest, underwater decomposition of the submerged vegetation produced hydrogen sulfide that killed fish and drove out villagers over a wide area. Acidified water from this reservoir ruined the turbine blades, making the dam useless for power generation. A recent study of one reservoir in Brazil suggested that decaying vegetation produced more greenhouse gases (carbon dioxide and methane) than would have come from generating an equal amount of energy by burning fossil fuels.

Floating water hyacinths (rare on free-flowing rivers) have already spread over reservoir surfaces behind the Tucurui Dam on the Amazon River in Brazil, impeding navigation and fouling machinery. Herbicides sprayed to remove aquatic vegetation have contaminated water supplies. Herbicides used to remove forests before dam gates closed caused similar pollution problems. Schistosomiasis, caused by parasitic flatworms called blood flukes (chapter 8), is transmitted to humans by snails that thrive in slow-moving, weedy tropical waters behind these dams. It is thought that 14 million Brazilians suffer from this debilitating disease.

As mentioned before, dams displace indigenous people. The Narmada Valley project in India will drown 150,000 ha of tropical forest and displace 1.5 million people, mostly tribal minorities and low-caste hill people. The Akosombo Dam built on the Volta River in Ghana nearly 20 years ago displaced 78,000 people from 700 towns. Few of these people ever found another place to settle, and those still living remain in refugee camps and temporary shelters. The Cree First Nations people of Canada also have been displaced by massive hydroelectric projects, most notably the James Bay project in Quebec and the Churchill/Nelson River diversion in Manitoba.

In tropical climates, large reservoirs often suffer enormous water losses. Lake Nasser, formed by 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 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. As in South America, schistosomiasis is an increasingly serious problem.

If big dams—our traditional approach to hydropower—have so many problems, how can we continue to exploit the great potential of hydropower? Fortunately, there is an alternative to gigantic dams and destructive impoundment reservoirs. Small-scale, **low-head hydropower** technology can extract energy from small headwater dams that cause much less damage than larger projects. Some modern, high-efficiency turbines can even operate on **run-of-the-river flow.** Submerged directly in the stream and small enough not to impede navigation in most cases, these turbines don't require a dam or diversion structure and can generate useful power with a current of only a few kilometers per hour. They also cause minimal environmental damage and don't interfere with fish movements, including spawning migration. **Micro-hydro generators** operate on similar principles but are small enough to provide economical power for a single home. If you live close to a small stream or river that runs year-round and you have sufficient water pressure and flow, hydropower is probably a cheaper source of electricity for you than solar or wind power (fig. 20.26).

Small-scale hydropower systems also can cause abuses of water resources. The Public Utility Regulatory Policies Act of 1978 included economic incentives to encourage small-scale energy projects. As a result, thousands of applications were made to dam or divert small streams in the United States. Many of these projects have little merit. All too often, fish populations,

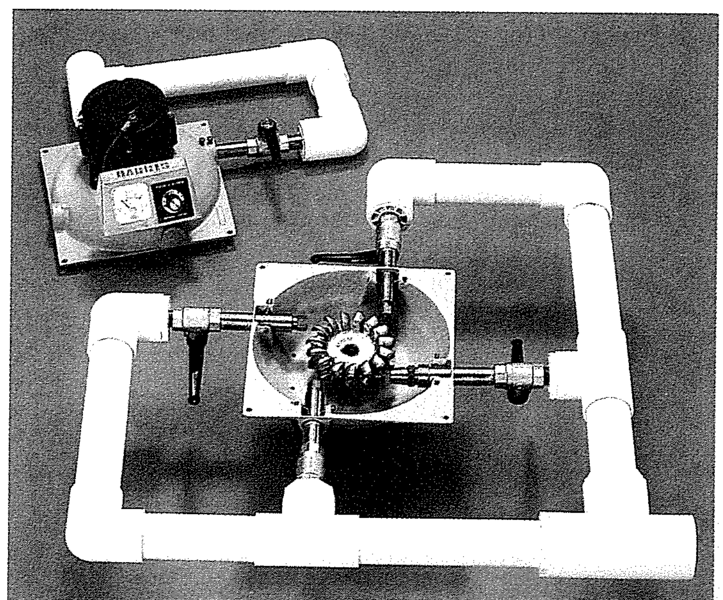

FIGURE 20.26 Solar collectors capture power only when the sun shines, but hydropower is available 24 hours a day. Small turbines such as this one can generate enough power for a single-family house with only 15 m (50 ft) of head and 200 l (50 g) per minute flow. The turbine can have up to four nozzles to handle greater water flow and generate more power.

aquatic habitat, recreational opportunities, and the scenic beauty of free-flowing streams and rivers are destroyed primarily to provide tax benefits for wealthy investors.

Wind energy is our fastest growing renewable source

Wind power played a crucial role in the settling of the American West, much of which has abundant underground aquifers, but little surface water. The strong, steady winds blowing across the prairies provided the energy to pump water that allowed ranchers and farmers to settle the land. By the end of the nineteenth century, nearly every farm or ranch west of the Mississippi River had at least one windmill, and the manufacture, installation, and repair of windmills was a major industry. The Rural Electrification Act of 1935 brought many benefits to rural America, but it effectively killed wind power development, and shifted electrical generation to large dams and fossil fuel-burning power plants. It's interesting to speculate what the course of history might have been if we had not spent trillions of dollars on fossil fuels and nuclear power, but instead had invested that money on small-scale, renewable energy systems.

The oil price shocks of the 1970s spurred a renewed interest in wind power. In the 1980s, the United States was a world leader in wind technology, and California hosted 90 percent of all wind power generators in the world. Poor management, technical flaws, and overdependence on subsidies, however, led to bankruptcy of many of the most important companies of that era, including Kenetech, once the world's largest manufacturer of wind generators. Now European companies dominate this (U.S.) $1 billion per year market.

Modern wind machines are far different from those employed a generation ago (fig. 20.27) The largest wind turbines now being built have 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 5,000 typical American homes. Out of commission for maintenance only about three days per year, many 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. Currently, wind farms are the cheapest source of *new* power 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. As table 20.3 shows, when the land consumed by mining is taken into account, 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.

Wind could meet all our energy needs

As this chapter's opening story shows, wind power offers an enormous potential for renewable energy. The World Meteorological Organization estimates that 80 million MW of wind power could be developed economically worldwide. This would be five times the total current global electrical generating capacity. Wind has a number of advantages over most other power sources. Wind farms have much shorter planning and construction times than fossil fuel or nuclear power plants. Wind generators are modular (more turbines can be added if loads grow) and they have no fuel costs or air emissions. In the past decade, total wind generating capacity has increased 15-fold making it the fastest growing energy source in the world. With 75,000 MW of installed capacity in 2007, wind power is making a valuable contribution to reducing global warming. Wind does have limitations, however. Like solar energy, it is an intermittent source. Furthermore, not every place has strong enough or steady enough wind to make this an economical resource. Although modern windmills are more efficient than those of a few years ago, it takes a wind velocity between 7 m per second (16 mph) and 27 m per second (60 mph) to generate useful amounts of electricity.

In places like the Netherlands, which has winds above 16 mph an average of 245 days per year, windmills have long been recognized as a valuable energy source for pumping water and

FIGURE 20.27 Renewable energy sources, such as wind, solar energy, geothermal power, and biomass crops, could eliminate our dependence on fossil fuels and prevent extreme global climate change, if we act quickly.

TABLE 20.3

Jobs and Land Required for Alternative Energy Sources

Technology	Land Use (m^2 per Gigawatt-Hour for 30 Years)	Jobs (per Terawatt-Hour per Year)
Coal	3,642	116
Photovoltaic	3,237	175
Solar thermal	3,561	248
Wind	1,335	542

Source: Lester R. Brown, 1991.

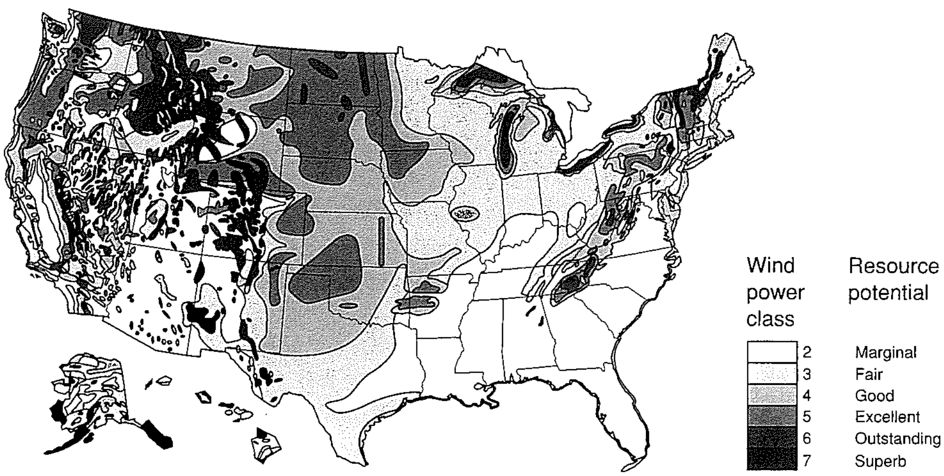

FIGURE 20.28 United States wind resource map. Mountain ranges and areas of the High Plains have the highest wind potential, but much of the country has a fair to good wind supply.
Source: Data from U.S. Department of Energy.

grinding grain. Germany, with 20,600 MW of installed capacity, now gets one-third of its electricity from wind power, and is now the world leader in this technology. Spain and the United States are tied for second with 11,600 MW each. India is fourth, with 6,300 MW. China has half as much installed capacity as India, but has potential for vastly more. The World Energy Council predicts that wind generating capacity could grow another tenfold by 2020.

While Europe, with its high population density, is focusing most attention to offshore wind farms, the bulk of North America's wind potential is situated across the Great Plains. Compared to offshore installations, which are costly because of the need to operate in deep water and withstand storms and waves, wind tower construction on land is relatively simple and cheap. There also is growing demand for wind projects from farmers, ranchers, and rural communities because of the economic benefits that wind energy brings. 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. Seven Midwestern states—North Dakota, Texas, Kansas, South Dakota, Montana, Iowa, and Minnesota—all now have at least 1,000 MW of wind power, but wind-energy experts estimate this is less than 1 percent of their ultimate potential (fig. 20.28).

With each tower taking only about a 0.1 ha (0.25 acre) of cropland, farmers find that they 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. Cooperatives are springing up to help landowners finance, build, and operate their own wind generators. About 20 Native American tribes, for example, have formed a coalition to study wind power. Together, their reservations (which were sited 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 capacity.

There are problems with wind energy. In some places, high bird 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. Some people object to the sight of large machines looming on the horizon. To others, however, windmills offer a welcome alternative to nuclear or fossil fuel-burning plants.

Many of the places most appropriate for wind development are far from the urban centers where power is needed (a major reason why people didn't settle in extremely windy places, is the wind). This means that some method is needed to transfer wind-generated power to the market. Currently, the only way to do that is high-voltage power lines (fig. 20.29). There may be more resistance to building thousands of kilometers of new power lines than to the wind farms themselves. An attractive alternative is to use the electricity from wind power to split water into hydrogen and oxygen gas. The gas could then be pumped through underground gas pipes to the city, where it could be used in fuel cells.

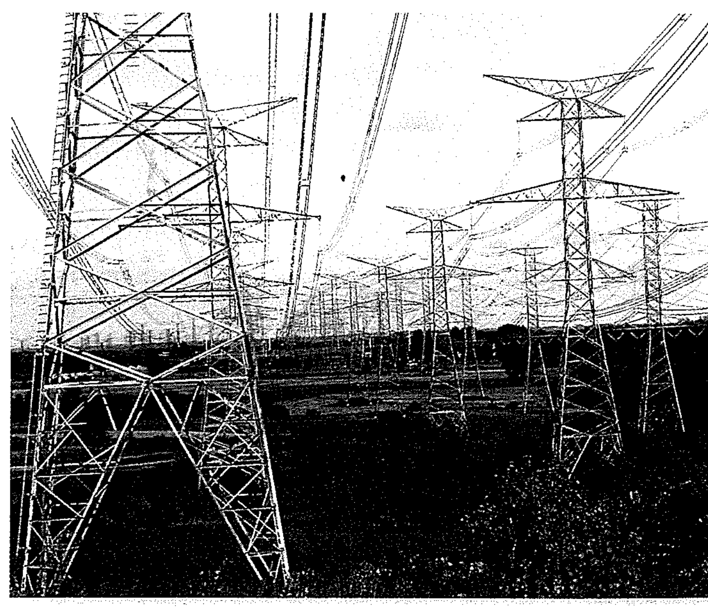

FIGURE 20.29 Dependence on wind or solar energy may require a vastly increased network of high-voltage power lines, many of which will cross places where people treasure now-unspoiled vistas.

Small windmills can generate enough electricity for a single home or farm, and are generally the least expensive form of renewable energy, if the winds are strong and steady enough in your area. The problem is how to store energy for windless days. Buying enough batteries to provide power for several days can be exorbitantly expensive, not to mention bulky and difficult to maintain. If you're able to hook up to the utility grid, the best solution to this problem is what's called reverse metering, in which you sell electricity back to your utility when you have a surplus and then draw from them when you have a shortage. If your system is sized right, it should pay for itself in about five years if wind speeds in your area are favorable.

Think About It

Some people object to the sight of giant windmills. They think it's an intrusion on the land and spoils the view. Yet those same people don't object to other forms of modern technology. Is this resistance just because wind power is new, or is there something truly different about it?

Geothermal heat, tides, and waves could be valuable resources

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.

While few places have geothermal steam, the earth's warmth can help reduce energy costs nearly everywhere. Pumping water through 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. 20.30). This can cut home heating costs by half in many areas, and pay for itself in five years.

Engineers are now exploring deep wells for community geothermal systems. Drilling 2,000 m (6,000 ft) in the American West gets you into rocks above 100°C. Fracturing them to expose more surface area, and pumping water in can produce enough steam to run an electrical generator at a cost significantly lower than conventional fossil fuel or nuclear power. The well is no more expensive than most oil wells, and the resource is never exhausted. Currently, about 60 new geothermal energy projects are being developed in the United States. This source could provide a significant energy supply eventually.

Ocean tides and waves 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

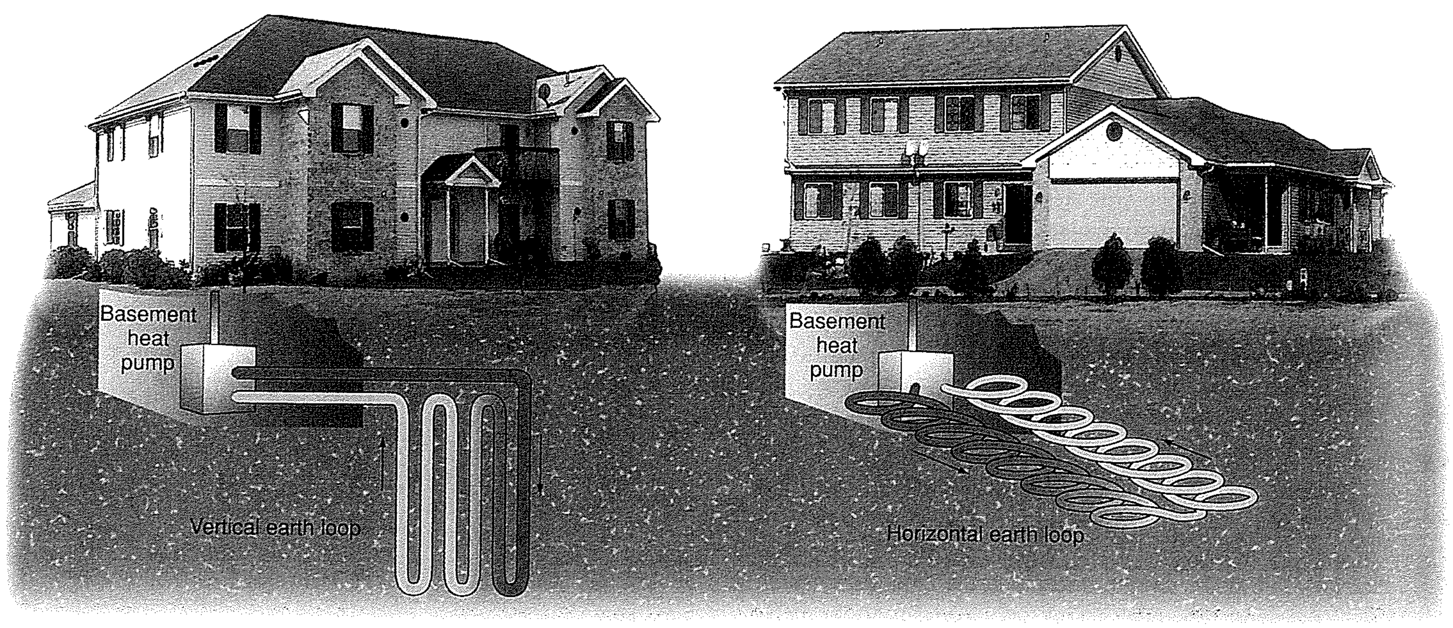

FIGURE 20.30 Geothermal energy can cut heating and cooling costs by half in many areas. In summer (shown here), warm water is pumped through buried tubing (earth loops) where it is cooled by constant underground temperatures. In winter, the system reverses and the relatively warm soil helps heat the house. Where space is limited (*left*), earth loops can be vertical. If more space is available (*right*) the tubing can be laid in shallow horizontal trenches. A heat exchanger concentrates heat, so water entering the house is far warmer than the ground temperature.

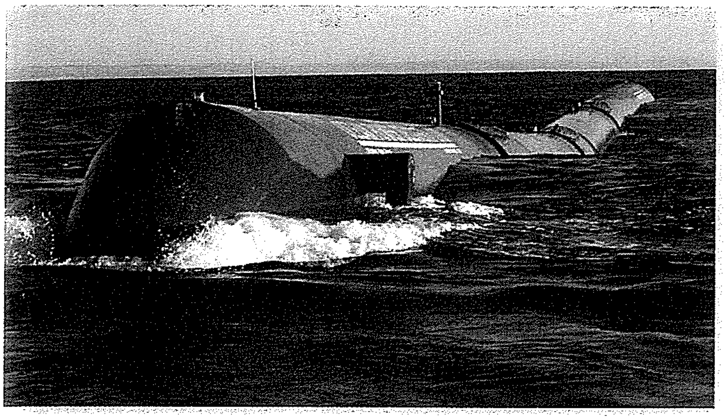

FIGURE 20.31 The Pelamis wave converter (named after a sea snake) is a 125 m long and 3.5 m diameter tube-hinged, so it undulates as ocean swells pass along it. This motion drives pistons that turn electrical generators. Energy experts calculate that capturing just 1 to 2 percent of global wave power could supply at least 16 percent of the world's electrical demand.

tidal periods often cause problems in integrating this energy source into the electric utility grid. Nevertheless, demand has kept some plants running 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 designs being explored include oscillating water columns that push or pull air through a turbine, and 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. It's difficult to design a mechanism that can survive the worst storms.

An interesting new development in this field is the Pelamis wave-power generator developed by the Scottish start-up company Ocean Power Delivery (fig. 20.31). The first application of this technology is now being built 5 km off the coast of Portugal. It will use three units capable of producing some 2.25 MW of electricity, or enough to supply 1,500 Portuguese households. If preliminary trials go well, plans are to add 40 more units in a year or two. 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 power, which is carried to shore by underwater cables.

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.

Ocean thermal electric conversion might be useful

Temperature differentials between upper and lower layers of the ocean's water also are a potential source of renewable energy. In a closed-cycle **ocean thermal electric conversion (OTEC)** system, heat from sun-warmed upper ocean layers is used to evaporate a working fluid, such as ammonia or Freon, which has a low boiling point. The pressure of the gas produced is high enough to spin turbines to generate electricity. Cold water then is pumped from the ocean depths to condense the gas.

As long as a temperature difference of about 20°C (36°F) exists between the warm upper layers and cooling water, useful amounts of net power can, in principle, be generated with one of these systems. This differential corresponds, generally, to a depth of about 1,000 m in tropical seas. The places where this much temperature difference is likely to be found close to shore are islands that are the tops of volcanic seamounts, such as Hawaii, or the edges of continental plates along subduction zones (chapter 14) where deep trenches lie just offshore. The west coast of Africa, the south coast of Java, and a number of South Pacific islands, such as Tahiti, have usable temperature differentials for OTEC power.

Although their temperature differentials aren't as great as the ocean, deep lakes can have very cold bottom water. Ithaca, New York, has recently built a system to pump cold water out of Lake Cayuga to provide natural air conditioning during the summer. Cold water discharge from a Hawaiian OTEC system has been used to cool the soil used to grow cool-weather crops such as strawberries.

Conclusion

None of the renewable energy sources discussed in this chapter are likely to completely replace fossil fuels and nuclear power in the near future. They could, however, make a substantial collective contribution toward providing us with the conveniences we crave in a sustainable, environmentally friendly manner. They could also make us energy independent and balance our international payment deficit.

The World Energy Council projects that renewables could provide about 40 percent of world cumulative energy consumption under an idealized "ecological" scenario assuming that political leaders take global warming seriously and pass taxes to encourage conservation and protect the environment (fig. 20.32). This scenario also envisions measures to shift wealth from the north to south, and to enhance economic equity. 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.

Rising fuel prices and increasing dependence on imported oil have prompted demands for a U.S. energy policy. Environmentalists point to the dangers of air pollution, global climate change, and other environmental problems associated with burning of fossil fuels. Businesses stress the importance of a reliable energy supply for economic growth. While both call for a new policy, they disagree on what it should contain. Conservatives tend to favor increasing production and easing regulations on power plant operation and transmission-line siting, rather than limiting demand. Progressives, on the other hand, prefer conservation measures such as forcing automakers to increase average fuel efficiency of cars and light trucks and providing heating bill assistance for low-income households.

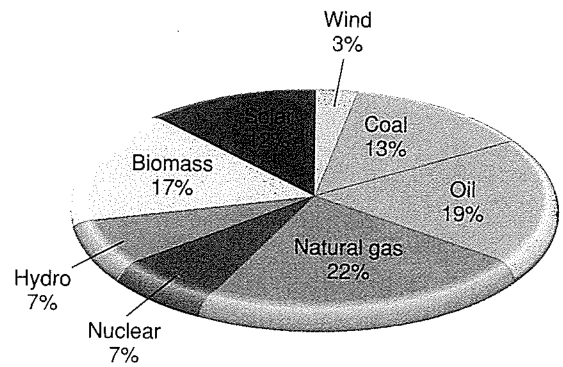

FIGURE 20.32 Idealized "ecological" scenario for cumulative world energy consumption, 2000 to 2100.
Source: World Energy Council, 2002.

What path do you think we should take to achieve an ideal energy future?

Reviewing Learning Outcomes

By now you should be able to explain the following points:

20.1 Remember that conservation can help us meet our energy needs.
- There are many ways to save energy.
- Transportation could be far more efficient.
- Cogeneration produces both electricity and heat.

20.2 Explain how we could tap solar energy.
- Solar collectors can be passive or active.
- Storing solar energy is problematic.

20.3 Discuss high-temperature solar energy.
- Simple solar cookers can save energy.
- Utilities are promoting renewable energy.
- Photovoltaic cells capture solar energy.
- Electrical energy is difficult and expensive to store.

20.4 Grasp the potential of fuel cells.
- All fuel cells have similar components.
- Several different electrolytes can be used in fuel cells.

20.5 Explain how we get energy from biomass.
- We can burn biomass.
- Fuelwood is in short supply in many less-developed countries.
- Dung and methane provide power.
- Biofuels could replace some oil-based energy.
- Should we use food for fuel?

20.6 Investigate energy from the earth's forces.
- Falling water has been used as an energy source since ancient times.
- Wind energy is our fastest growing renewable source.
- Wind could meet all our energy needs.
- Geothermal heat, tides, and waves could be valuable resources.
- Ocean thermal electric conversion might be useful.

Practice Quiz

1. Describe five ways that we could conserve energy individually or collectively.
2. Explain the principle of net energy yield. Give some examples.
3. What is the difference between active and passive solar energy?
4. How do photovoltaic cells generate electricity?

5. What is a fuel cell and how does it work?
6. Describe some problems with wood burning in both industrialized nations and developing nations.
7. How is methane made? Give an example of a useful methane source.
8. What are some advantages and disadvantages of large hydroelectric dams?
9. What are some examples of biomass fuel other than wood?
10. Describe how tidal power or ocean wave power generate electricity.

Critical Thinking and Discussion Questions

1. What alternative energy sources are most useful in your region and climate? Why?
2. What can you do to conserve energy where you live? In personal habits? In your home, dormitory, or workplace?
3. Do you think building wind farms in remote places, parks, or scenic wilderness areas would be damaging or unsightly?
4. If you were the energy czar of your state, where would you invest your budget?
5. What could (or should) we do to help developing countries move toward energy conservation and renewable energy sources? How can we ask them to conserve when we live so wastefully?

DATA analysis Energy Calculations

Most college students either already own or are likely to buy an automobile and a computer sometime soon. How do these items compare in energy usage? Suppose that you were debating between a high-mileage car, such as the Honda Insight, or a sport utility vehicle, such as a Ford Excursion. How do the energy requirements of these two purchases measure up? To put it another way, how long could you run a computer on the energy you would save by buying an Insight rather than an Excursion?

Here are some numbers you need to know. The Insight gets about 75 mpg, while the Excursion gets about 12 mpg. A typical American drives about 15,000 mi per year. A gallon of regular, unleaded gasoline contains about 115,000 Btu on average. Most computers use about 100 watts of electricity. One kilowatt-hour (kWh) = 3,413 Btu.

1. How much energy does the computer use if it is left on continuously? (You really should turn it off at night or when it isn't in use, but we'll simplify the calculations.)

   100 watt/h × 24 h/day × 365 days/yr = _____ kWh/yr

2. How much gasoline would you save in an Insight, compared with an Excursion?

   a. Excursion:

      15,000 mi/yr ÷ 12 mpg = _____ gal/yr

   b. Insight:

      15,000 mi/yr ÷ 75 mpg = _____ gal/yr

   c. Gasoline savings ($a - b$) = _____ gal/yr

   d. Energy savings:

      (gal × 115,000 Btu) = _____ Btu/yr

   e. Converting Btu to kWh:

      (Btu × 0.00029 Btu/kWh) = _____ kWh/yr saved

3. How long would the energy saved run your computer? kWh/yr saved by Insight ÷ kWh/yr consumed by computer = _____

For Additional Help in Studying This Chapter, please visit our website at www.mhhe.com/cunningham10e. You will find additional practice quizzes and case studies, flashcards, regional examples, place markers for Google Earth™ mapping, and an extensive reading list, all of which will help you learn environmental science.