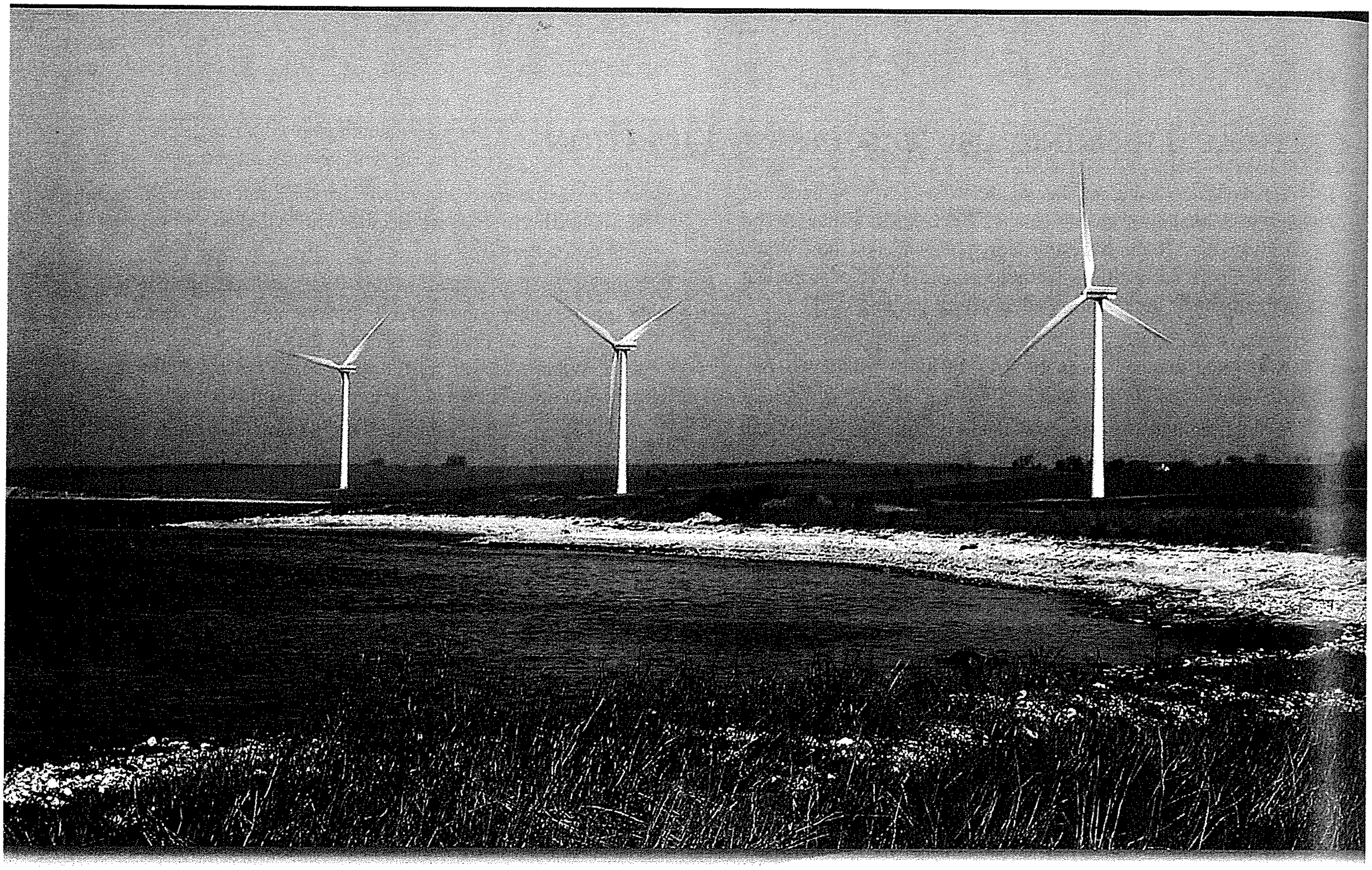


Windmills supply all the electricity used on Denmark's Ærø Island, while solar and biomass energy provide space heating and vehicle fuel. Altogether, 100 percent of the island's energy comes from renewable sources.

C H A P T E R

Sustainable Energy

Two roads diverged in a wood, and I—I took the one less traveled by, And that has made all the difference.

—Robert Frost—

LEARNING OUTCOMES

After studying this chapter, you should be able to:

20.1 Remember that conservation can help us meet our energy needs.

20.2 Explain how we could tap solar energy.

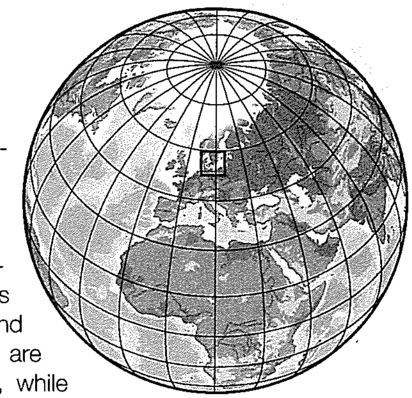
20.3 Discuss high-temperature solar energy.

20.4 Grasp the potential of fuel cells.

20.5 Explain how we get energy from biomass.

20.6 Investigate energy from the earth's forces.

Case Study Renewable Energy Islands



Denmark has substantial oil and gas supplies under the North Sea, but the Danes have chosen to wean themselves away from dependence on fossil fuels. Currently the world leader in renewable energy, Denmark now gets 20 percent of its power from solar, wind, and biomass. Some parts of this small, progressive country have moved even further toward sustainability. One of the most inspiring examples of these efforts are the small islands of Samsø and Ærø, which now get 100 percent of their energy from renewable sources.

Samsø and Ærø lie between the larger island of Zealand (home to Copenhagen) and the Jutland Peninsula. The islands are mostly agricultural. Together, they have an area of about 200 km^2 (77 mi^2) and a population of about 12,000 people. In 1997, Samsø and Ærø were chosen in a national competition to be renewable energy demonstration projects. The first step in energy independence is conservation, As you'll learn in this chapter, Denmark uses roughly half as much energy per person as the United States, although by most measures the Danes have a higher standard of living than most Americans. Danish energy conservation is achieved with high-efficiency appliances, superior building insulation, high-mileage vehicles, and other energy-saving measures. Most homes are clustered in small villages, both to save agricultural land and to facilitate district heating. Living closely together also makes having a private automobile less necessary.

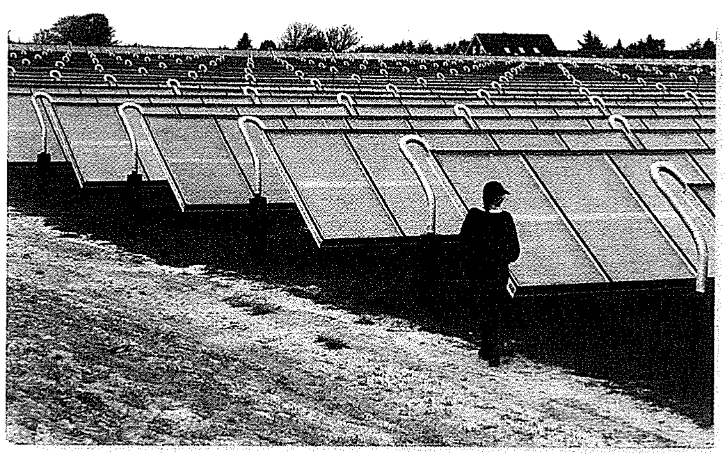


FIGURE 20.1 A 19,000 m^2 array of solar water heaters provides space heating for the town of Marstal on Ærø Island.

Some 30 large wind generators provide 100 percent of Samsø and Ærø's electricity. Two-thirds of these windmills are located offshore, and are publicly owned. The 11 onshore wind turbines are mostly privately owned, but a share of the profits is used to finance other community energy projects. Space heating accounts for about one-third of the energy consumption on the islands. District heating systems provide most of this energy. Several large solar collector arrays supply about half the hot water for space heating and household use (fig. 20.1). Biomass-based (straw, wood chips, manure) systems supply the remainder of the island's heating needs. Some of this biomass comes from energy crops (fast-growing elephant grass and hybrid poplars, for example, are grown on marginal farmland), while the rest comes from agricultural waste. Biodiesel (primarily from rapeseed oil) fuels farm tractors and ferries, while most passenger vehicles are electric.

Geothermal pumps supplement the solar water heaters, and in one village a recently closed landfill produces methane that is used to run a small electric generator. Nuclear power is considered an unacceptable option in Denmark and doesn't feature in current energy plans. Samsø and Ærø have won numerous prizes and awards for their pioneering conversion to renewable energy, Over the past 20 years, as a result of other projects like those on Samsø and Ærø, both Denmark's fossil fuel consumption and their greenhouse gas emissions have remained constant. All of us could learn from their example.

Many other countries, both in Europe and elsewhere in the world, are turning to renewable energy to reduce their dependence on environmentally damaging and politically unstable fossil fuels. The European Renewable Energy Council suggests that we might obtain half our global energy supply by the middle of this century. In this chapter, we'll look at what our options are for finding environmentally and socially sustainable ways to meet our energy needs.

20.1 Conservation

As the previous chapter and the opening story of this chapter suggest, we urgently need to move toward sustainable, environmentally friendly, affordable, politically progressive energy sources for a number of reasons. One of the easiest ways to avoid energy shortages and to relieve environmental and health effects of our current energy technologies is simply to use less. We have already seen the benefits of conservation. Energy consumption rose rapidly in the United States in the 1960s, but the price shocks of the 1970s brought energy use down sharply (fig. 20.2). Although economic growth resumed in the 1980s and 1990s, conservation kept energy consumption relatively constant.

There are many ways to save energy

Much of the energy we consume is wasted. This statement isn't a simple admonishment to turn off lights and turn down furnace thermostats in winter; it's a technological challenge. 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. Of the energy we do extract from primary resources, however, much is

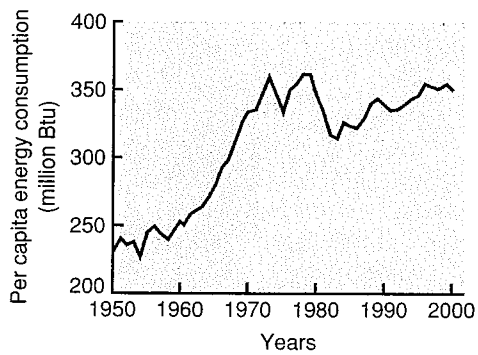


FIGURE 20.2 Per capita energy consumption in the United States rose rapidly in the 1960s. Price shocks in the 1970s encouraged conservation. Although GDP continued to grow in the 1980s and 1990s, higher efficiency kept per capita consumption relatively constant.
Source: U.S. Department of Energy.

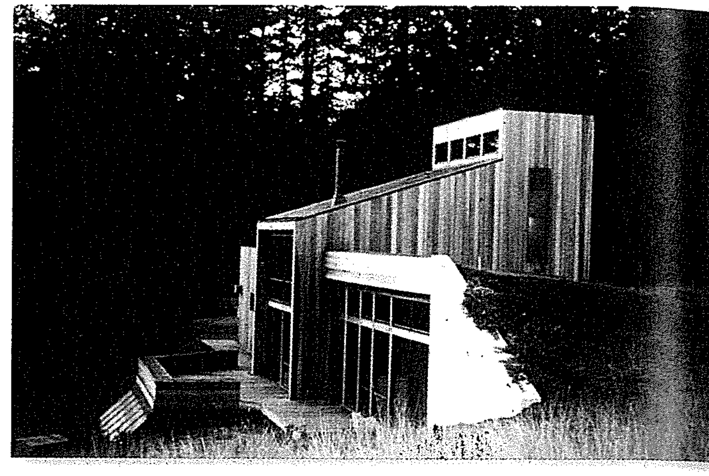


FIGURE 20.3 Earth-sheltered homes take advantage of the stable temperatures and insulating qualities of the earth. This house has south-facing windows for maximum solar gain, and high clerestory windows that give light to the back of the house as well as summer ventilation.

used for frankly trivial or extravagant purposes. As chapter 19 shows, several European countries have higher standards of living than the United States, and yet use 30 to 50 percent less energy.

Many conservation techniques are relatively simple and highly cost effective. Compact fluorescent bulbs, for example, produce four times as much light as an incandescent bulb of the same wattage, and last up to ten times as long. Although they cost more initially, total lifetime savings can be $30 to $50 per fluorescent bulb.

Light-emitting diodes (LEDs) also are even more efficient, consuming 90 percent less energy and lasting hundreds of times as long as ordinary lightbulbs. They can produce millions of colors and be adjusted in brightness to suit ambient conditions. They are being used now in everything from flashlights and Christmas lights, to advertising signs, brake lights, exit signs, and street lights. New York city has replaced 11,000 traffic lights with LEDs. It also replaced 180,000 old refrigerators with new energy-saving models.

Many improvements in domestic energy efficiency have occurred in the past decade. Today's average new home uses one-half the fuel required in a house built in 1974, but much more can be done. Household energy losses can be reduced even further by better insulation, double or triple glazing of windows, thermally efficient curtains or window coverings, and by sealing cracks and loose joints. 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. It doesn't take much skill or investment to caulk around doors, windows, foundation joints, electrical outlets, and other sources of air leakage.

According to new national standards, all new washing machines have to use 35 percent less water than older models. This makes them a little more expensive, but will pay back in seven years. It also cuts water use in the United States by 40 trillion liters (10.5 trillion gallons) per year and saves more electricity every year than is used to light all the homes in the United States. Air conditioners also are required to be about 20 percent more efficient than previous models.

For even greater savings, new houses can be built with extra thick superinsulated walls, air-to-air heat exchangers to warm incoming air, and even double-walled sections that create a "house within a house." The R-2000 program in Canada details how energy conservation can be built into homes. Special 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.

Orienting homes so that living spaces have passive solar gain in the winter and are shaded by trees or roof overhang in the summer also helps conserve energy. Earth-sheltered homes built into the south-facing side of a slope or protected on three sides by an earth berm are exceptionally efficient energy savers because they maintain relatively constant subsurface temperatures (fig. 20.3). Sod roofs provide good insulation, prevent rain runoff, and last longer than asphalt shingles. Because they are heavier, however, they need stronger supports.

Straw-bale construction offers both high insulating qualities and a renewable, inexpensive building material that can be assembled by amateurs (fig. 20.4). This isn't a new technique. Settlers on the Great Plains built straw-bale houses a century ago because they didn't have wood. Some of those houses are still standing. The bales are strong and will support the roof without any additional timber framing. They must be thoroughly waterproofed, however, with stucco, adobe, or plaster both inside and out so the straw doesn't decay. It's also important to seal them so mice and other vermin can't take up residence. The thick walls are terrific sound insulators as well as highly energy efficient. The cost can be less than a conventionally built home.

One of the most direct and immediate ways that individuals can save energy is to turn off appliances. Few of us realize how much electricity is used by appliances in a standby mode. You

FIGURE 20.4 Carolyn Roberts and her sons build a straw-bale house near Tucson, Arizona.

TABLE 20.1

Typical Net Efficiencies of Some Power Sources

	Yield (Percent)
Electric Power Plants	
Hydroelectric (best case)	90
Co-generation	80
Fuel cell (hydrogen)	80
IGCC	45
Coal-fired generator	38
Oil-burning generator	38
Nuclear generator	30
Photovoltaic solar	15

Source: U.S. Department of Energy.

may think you've turned off your TV, DVD player, cable box, or printer, but they're really continuing to draw power in an "instant-on" mode. For the average home, standby appliances can represent up to 25 percent of the monthly electric bill. Home office equipment including computers, printers, cable modems, copiers, etc., usually are the biggest energy consumers (fig. 20.5). Putting your computer to sleep saves about 90 percent of the energy it uses when fully on, but turning it completely off is even better.

Industrial energy savings are another important part of 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.

Energy efficiency is a measure of energy produced compared to energy consumed. Table 20.1 shows the typical energy efficiencies of some power sources. Thermal-conversion machines, such as steam turbines in coal-fired or nuclear power plants, can turn no more than 40 percent of the energy in their primary fuel into electricity or mechanical power because of the need to reject waste heat. Does this mean that we can never increase the efficiency of fossil fuel use? No. Some waste heat can be recaptured and used for space heating, raising the net yield to 80 or 90 percent. The integrated gasification combined cycle (IGCC) process described in chapter 19 is an example of capture of waste heat. In another kind of process, fuel cells convert the chemical energy of a fuel directly into electricity without an intermediate combustion cycle. Since this process is not limited by waste heat elimination, its efficiencies can approach 80 percent with such fuel as hydrogen gas or methane. We'll discuss the special case of biofuel efficiency later in this chapter.

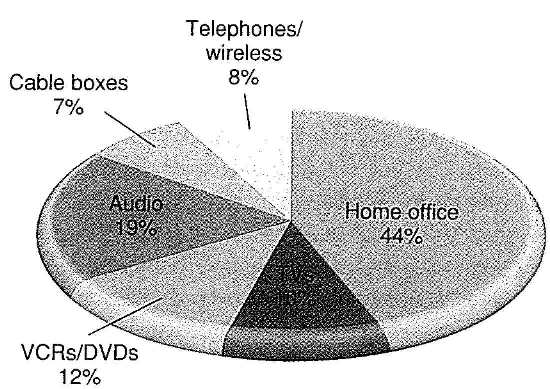


FIGURE 20.5 Typical standby energy consumption by household electrical appliances.
Source: U.S. Department of Energy.

Transportation could be far more efficient

One of the areas in which most of us can accomplish the greatest energy conservation is in our transportation choices. You may not be able to build an energy-efficient house or persuade your utility company to switch from coal or nuclear to solar energy, but you can decide every day how you travel to school, to work, or for shopping or entertainment. Automobiles and light trucks account for 40 percent of the U.S. oil consumption and produce one-fifth of its carbon dioxide emissions. According the U.S. EPA, raising the average fuel efficiency of the passenger fleet by 3 miles per gallon (approx. 1.4 l/100 km), would save American consumers about $25 billion a year in fuel costs, reduce carbon dioxide emissions by 140 million metric tons per year, and save more oil than the maximum expected production from Alaska's Arctic National Wildlife Refuge.

The Bureau of Transportation Statistics reports that there are now more vehicles in the United States (214 million) than licensed drivers (190 million). More importantly, those vehicles are used for an average of 1 billion trips per day. Many of us drive now for errands or short shopping trips that might have previously been made on foot. Some of that is due to the design of our cities (chapter 22). Suburban subdivisions have replaced compact downtown centers in most cities. Shopping areas are surrounded by busy streets and vast parking lots that are highly pedestrian unfriendly. But sometimes we use fuel inefficiently simply because we haven't thought about alternatives. The Census Bureau reports that three-quarters of all workers commute alone in private vehicles. Less than 5 percent use public transportation or carpool, and a mere 0.38 percent walk or travel by bicycle.

In response to the 1970s oil price shocks, automobile gas-mileage averages in the United States more than doubled from 13.3 mpg in 1973 to 25.9 mpg in 1988. Unfortunately, falling fuel prices of the 1990s discouraged further conservation. By 2006, the average fuel economy of America's passenger fleet was only 22.1 mpg miles a gallon. Most of this decrease was due to the popularity of SUVs and light trucks, which now account for half of all passenger vehicle sales in the United States. According to the Environmental Protection Agency (EPA), in 2006, SUVs averaged 18.5 miles per gallon (mpg), and pickups averaged 17 mpg, while cars averaged 24.6 mpg. Conservationists argue that efficiency standards should be raised to 44 mpg for cars and 33 mpg for SUVs and light trucks.

What can you do if you want to be environmentally responsible? The cheapest, least environmentally damaging, and healthiest alternative for short trips is walking. You need to get some exercise every day, why not make walking part of it? Next, in terms of minimal expense and environmental impact, is an ordinary bicycle. For trips less than 2 km, it's often quicker to go by bicycle than to find a parking space for your car. While many cities have downgraded their mass transit systems, you might be surprised at the places you can go with this option.

If you're only making short, local trips, why not consider one of the high-efficiency mini cars? The Daimlerchrysler "smart car," for example, has been available in Europe for several years and has now been approved for sale in the United States (fig. 20.6). They get 60 mpg and produce far less pollution than the average full-size car. Easy to maneuver in crowded city streets, two or three of these mini-autos can be parked head-on in a standard parking space.

You probably already know that **hybrid gasoline-electric engines** offer the best fuel economy and lowest emissions of any currently available vehicles. During most city driving, they depend mainly on quiet, emission-free, battery-powered electric motors. A small gasoline engine kicks in to help accelerate or when the batteries need recharging. This extends their range compared to pure electric vehicles. In 2007, the Toyota Prius had the highest mileage rating of any automobile sold in America: 60 mpg (25 km/l) in city driving and 51 mpg (22 km/l) on the highway. Many automakers are now offering hybrid models. Ford claims that half their vehicles will have this option in a few years. You should be aware that some so-called "mild hybrids" only use the electrical generator and battery pack to run accessories, such as video players and computers, not to enhance mileage.

FIGURE 20.6 High-efficiency "smart" cars have been available for many years in Europe. Getting the equivalent of 60 mpg, they produce far less pollution than a typical American car. They are easy to maneuver in crowded city streets, and two can park in a standard parking space.

An even greater savings can be achieved by **plug-in hybrids.** Recharging the batteries from ordinary household current at night can allow these vehicles to travel up to 64 km (40 mi) on the electric motor alone. Since most Americans only drive about 30 km per day, they'd rarely have to buy any gasoline. In most places, electricity costs the equivalent of about 50 cents per gallon. This means that we'll be generating more electricity, but it's easier to capture pollutants and greenhouse gases at a single, stationary power plant than from thousands of individual, mobile vehicles. You can already buy after-market kits to convert an ordinary hybrid into a plug-in, but auto manufacturers threaten to void your warranty if you do so. Several automakers promise to have plug-ins on the market soon.

Diesels already make up about half the autos sold in Europe because of their superior efficiency. A light-weight, four-passenger, diesel roadster that gets up to 150 mpg (62.5 km/l) is now being sold in Europe for about 11,000 euros. Most Americans think of diesels as noisy, smoke-belching, truck engines, but recent advances have made them much cleaner and quieter than they were a generation ago. Ultra low-sulfur diesel fuel and effective tailpipe emission controls could make these engines nearly as clean and energy-efficient as hybrids. Perhaps best of all would be to have flex-fuel or diesel plug-in hybrids that could burn ethanol or biodiesel when they need fuel. That could make us entirely independent from imported oil.

Both the United States and the European Union have announced plans to spend billions of dollars on research and development of hydrogen fuel-cell-powered vehicles. Using hydrogen gas for fuel, these vehicles would produce water as their only waste product. We'll discuss how fuel cells work in more detail later in this chapter. Although prototype fuel cell vehicles are already being tested in several places, even the most optimistic predictions are that it will take at least 20 years for this technology to be mass produced at a reasonable cost. Although hydrogen fuel could be produced with electricity from remote wind or solar facilities, providing a convenient and inexpensive way to get surplus energy to market, most hydrogen currently is created from natural gas, making it no cleaner or more efficient than simply burning the gas directly. While not calling for an end to fuel cell research, conservation groups are urging the government not to abandon other useful technologies, such as hybrid engines and conventional pollution control, while waiting for fuel cells.

Think About It

What barriers do you see to walking, biking, or mass transit in your home town? How could cities become more friendly to sustainable transportation? Why not write a letter to your city leaders or the editor of your newspaper describing your ideas?

Cogeneration produces both electricity and 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 being renewed. The capacity for cogeneration more than doubled in the 1980s to about 30,000 megawatts (MW). District heating systems are being rejuvenated, and plants that burn municipal wastes are being studied. New combined-cycle coal-gasification plants or "mini-nukes" (chapter 19) offer high efficiency and clean operation that may be compatible with urban locations. Small neighborhood- or apartment building-sized power-generating units are being built that burn methane (from biomass digestion), natural gas, diesel fuel, or coal (fig. 20.7). The Fiat Motor Company makes a small generator for about $10,000 that produces enough electricity and heat for four or five energy-efficient houses. These units are especially valuable for facilities like hospitals or computer centers that can't afford power outages.

Although you may not be buying a new house or car for a few years, and you probably don't have much influence over industrial policy or utility operation, there are things that all of us can do to save energy every day (What Can You Do? p. 453).

FIGURE 20.7 A technician adjusts a gas microturbine that produces on-site heat and electricity for businesses, industry, or multiple housing units.

What Can You Do?

Some Things You Can Do to Save Energy

1. Drive less: make fewer trips, use telecommunications and mail instead of going places in person.
2. Use public transportation, walk, or ride a bicycle.
3. Use stairs instead of elevators.
4. Join a car pool or drive a smaller, more efficient car; reduce speeds.
5. Insulate your house or add more insulation to the existing amount.
6. Turn thermostats down in the winter and up in the summer.
7. Weatherstrip and caulk around windows and doors.
8. Add storm windows or plastic sheets over windows.
9. Create a windbreak on the north side of your house; plant deciduous trees or vines on the south side.
10. During the winter, close windows and drapes at night; during summer days, close windows and drapes if using air conditioning.
11. Turn off lights, television sets, and computers when not in use.
12. Stop faucet leaks, especially hot water.
13. Take shorter, cooler showers; install water-saving faucets and showerheads.
14. Recycle glass, metals, and paper; compost organic wastes.
15. Eat locally grown food in season.
16. Buy locally made, long-lasting materials.

20.2 Tapping Solar Energy

The sun serves as a giant nuclear furnace in space, constantly bathing our planet with a free energy supply. Solar heat 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 some 10,000 times all the commercial energy used each year. However, this tremendous infusion of energy comes in a form that, until this century, has been too diffuse and low in intensity to be used except for environmental heating and photosynthesis. But if we could devise cost-effective ways to use this vast power source, we would never again have to burn fossil fuels. Figure 20.8 shows solar energy levels over the United States for a typical summer and winter day.

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 (fig. 20.9). After cooling at night, these massive building materials maintain a comfortable daytime temperature within the house, even as they absorb external warmth.

A modern adaptation of this principle is a glass-walled "sunspace" or greenhouse on the south side of a building (fig. 20.10). 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. An interior, heat-absorbing wall called a Trombe wall is an effective passive

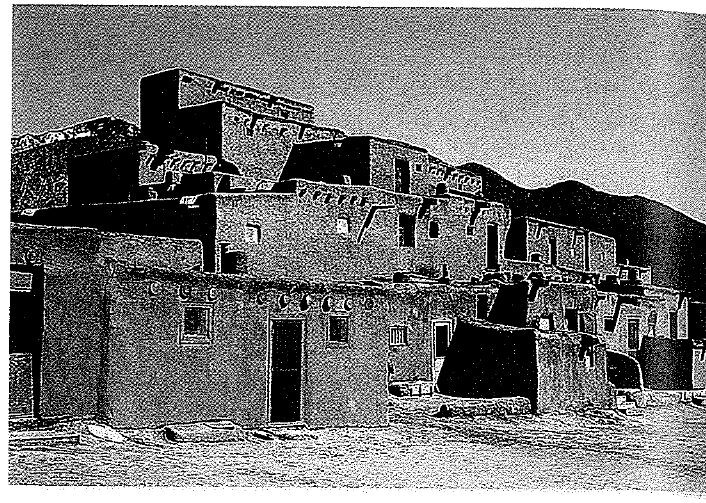


FIGURE 20.9 Taos Pueblo in northern New Mexico uses adobe construction to keep warm at night and cool during the day.

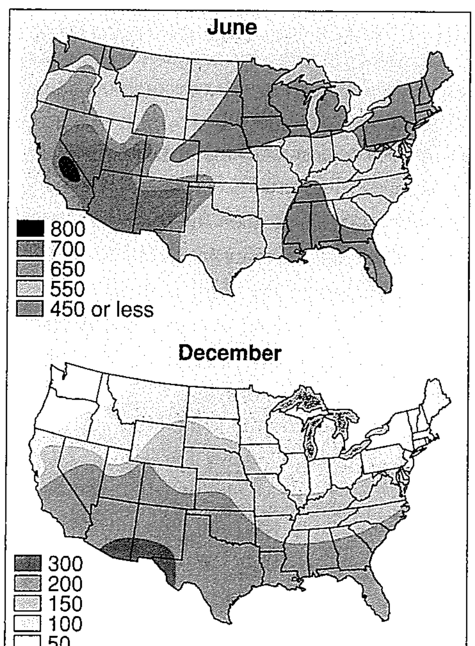


FIGURE 20.8 Average daily solar radiation in the United States in June and December. One langley, the unit for solar radiation, equals 1 cal/cm^2 of earth surface (3.69 Btu/ft^2).
Source: Data from National Weather Bureau, U.S. Department of Commerce.

FIGURE 20.10 The Adam Joseph Lewis Center for Environmental Studies at Oberlin College is designed to be self-sustaining even in northern Ohio's cool, cloudy climate. Large, south-facing windows let in sunlight, while 370 m^2 of solar panels on the roof generate electricity. A constructed wetland outside and a living machine inside (see fig. 18.27) purify wastewater.

heat collector. Some Trombe walls are built of glass blocks enclosing a water-filled space or water-filled circulation tubes so heat from solar rays can be absorbed and stored, while light passes through to inside rooms.

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. A fan circulates air over the hot surface and into the house through ductwork of the type used in standard forced-air heating. Alternatively, water can be pumped through the collector to pick up heat for space heating or to provide hot water. Water heating consumes 15 percent of the United States' domestic energy budget, so savings in this area alone can be significant. A simple flat panel with about 5 m^2 of surface can reach 95°C (200°F) and can provide enough hot water for an average family of four almost anywhere in the United States. In California, 650,000 homes now heat water with solar collectors. In Greece, Italy, Israel, and other countries where fuels are more expensive, up to 70 percent of domestic hot water comes from solar collectors. In Europe, municipal solar systems provide district heating for whole cities.

Storing solar energy is problematic

Sunshine doesn't reach us all the time, of course. How can solar energy be stored for times when it is needed? There are a number of options. In a climate where sunless days are rare and seasonal variations are minimal, a small, insulated water tank is a good solar energy storage system. For areas where clouds block the sun for days at a time or where energy must be stored for winter use, a large, insulated bin containing a heat-storing mass, such as stone, water, or clay, provides good solar energy storage. During the summer months, a fan blows the heated air from the collector into the storage medium. In the winter, a similar fan at the opposite end of the bin blows the warm air into the house. During the summer, the storage mass is cooler than the outside air, and it helps cool the house by absorbing heat. During the winter, it is warmer and acts as a heat source by radiating stored heat. In many areas, six or seven months' worth of thermal energy can be stored in 10,000 gallons of water or 40 tons of gravel, about the amount of water in a very small swimming pool or the gravel in two average-sized dump trucks.

20.3 High-Temperature Solar Energy

Parabolic mirrors are curved reflecting surfaces that collect light and focus it into a concentrated point. There are two ways to use mirrors to collect solar energy to generate high temperatures. One

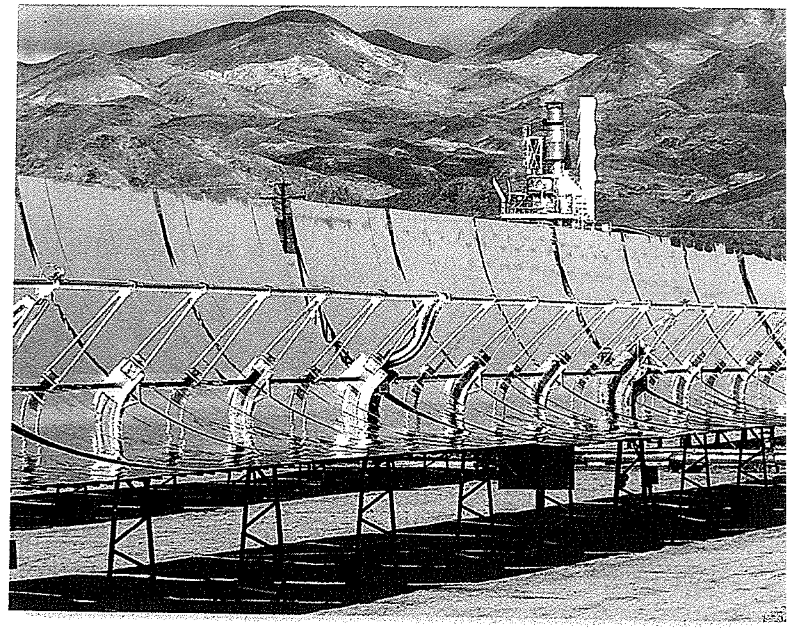


FIGURE 20.11 Parabolic mirrors focus sunlight on steam-generating tubes at this power plant in the California desert.

technique uses long curved mirrors focused on a central tube, containing a heat-absorbing fluid (fig. 20.11). Fluid flowing through the tubes reaches much higher temperatures than possible in a basic flat panel collector.

Another high-temperature system uses thousands of smaller mirrors arranged in concentric rings around a tall central tower. The mirrors, driven by electric motors, track the sun and focus its light on a heat absorber at the top of the "power tower" where molten salt 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 acres) mirror array should be able to generate 100 MW of clean, renewable power. The only power tower in the United States is Southern California Edison's Solar II plant in the Mojave Desert east of Los Angeles. Its 2,000 mirrors focused on a 100 m (300 ft) tall tower generates 10 MW or enough electricity for 5,000 homes at an operating cost far below that of nuclear power or oil. We haven't had enough experience with these facilities to know how reliable the mirrors, motors, heat absorbers, and other equipment will be over the long run.

If the entire U.S. electrical output came from such central tower solar steam generators, 60,000 km^2 of collectors would be needed. This is an area about half the size of South Dakota. It is less land, however, than would be strip mined in a 30-year period if all our energy came from coal or uranium. In contrast with windmill farms, which can be used for grazing or farming while also producing energy, mirror arrays need to be carefully protected and are not compatible with other land uses.

Simple solar cookers can save energy

Parabolic mirrors have been tested for home cooking in tropical countries where sunshine is plentiful and other fuels are scarce. They produce such high temperatures and intense light that they are dangerous, however. A much cheaper, simpler, and safer

FIGURE 20.12 A simple box of wood or cardboard, plastic, and foil can help reduce tropical deforestation, improve women's lives, and avoid health risks from smoky fires in developing countries. These inexpensive solar cookers could revolutionize energy use in developing tropical countries.

alternative is the solar box cooker (fig. 20.12). An insulated box costing only a few dollars, with a black interior and a glass or clear plastic lid, serves as a passive solar collector. Several pots can be placed inside at the same time. Temperatures only reach about 120°C (250°F) so cooking takes longer than an ordinary oven. Fuel is free, however, and the family saves hours each day usually spent hunting for firewood or dung. These solar ovens help reduce tropical forest destruction and reduce the adverse health effects of smoky cooking fires.

Utilities are promoting renewable energy

Energy policies in some states include measures to encourage conservation and alternative energy sources. Among these are: (1) "distributional surcharges" in which a small per kWh charge is levied on all utility customers to help renewable energy finance 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. Perhaps your state has some or all of these in place.

Iowa, for example, 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. Many utilities now offer renewable energy options. You agree to pay a couple of dollars extra on your monthly bill, and they promise to use the money to build or buy renewable energy. 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. Not all green pricing plans are as straightforward as this, however. Some utilities collect the premium rates for facilities that already exist or for energy sources, such as hydropower projects, that are technically "renewable" but still have adverse environmental effects.

Interestingly, some nonutility companies are investing in sustainable energy. BP, the company formerly known as British Petroleum, now says its initials stand for "Beyond Petroleum." It is investing in solar and other renewables. The company believes that the threat of global climate change requires us to search for new types of energy. Similarly, two European insurance companies, concerned about potential losses from storms and rising sea levels caused by global warming, are investing $5 million in Sunlight Power, a U.S. company that makes and services solar power systems for remote regions of developing countries where electric service is unavailable.

Photovoltaic cells capture solar energy

The photovoltaic cell offers an exciting potential for capturing solar energy in a way that will provide clean, versatile, renewable energy. This simple device has no moving parts, negligible maintenance costs, produces no pollution, and has a lifetime equal to that of a conventional fossil fuel or nuclear power plant.

Photovoltaic 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. 20.13). The photovoltaic effect, which is the basis of these devices, was first observed in 1839 by French physicist

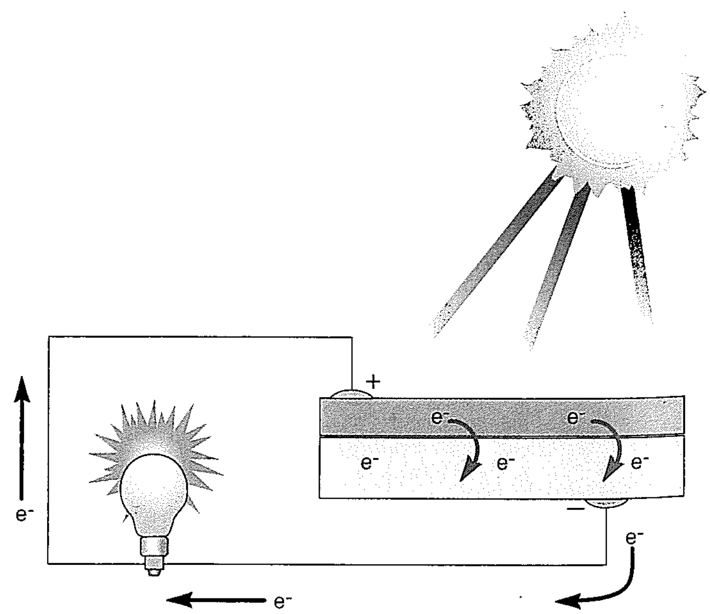


FIGURE 20.13 The operation of a photovoltaic cell. Boron impurities incorporated into the upper silicon crystal layers cause electrons (e-) to be released when solar radiation hits the cell. The released electrons move into the lower layer of the cell, thus creating a shortage of electrons, or a positive charge, in the upper layer and an oversupply of electrons, or negative charge, in the lower layer. The difference in charge creates an electric current in a wire connecting the two layers.

Alexandre-Edmond Becquerel, who also discovered radioactivity. His discovery didn't lead to any useful applications until 1954, when researchers at Bell Laboratories in New Jersey learned how to carefully introduce impurities into single crystals of silicon.

These handcrafted single-crystal cells were much too expensive for any practical use until the advent of the U.S. space program. In 1958, when *Vanguard I* went into orbit, its radio was powered by six palm-sized photovoltaic cells that cost $2,000 per peak watt of output, more than 2,000 times as much as conventional energy at the time. Since then, prices have fallen dramatically. In 1970, they cost $100 per watt; in 2007 they were less than $2.50 per watt. This makes solar energy cost-competitive with other sources in remote areas (more than 1 km from a power line).

Think About It

The 2005 U.S. Energy Bill had more than $12 billion in subsidies for the oil, coal, gas, and nuclear industries, but only one-sixth that much for renewable energy. Where might we be if that ratio had been reversed?

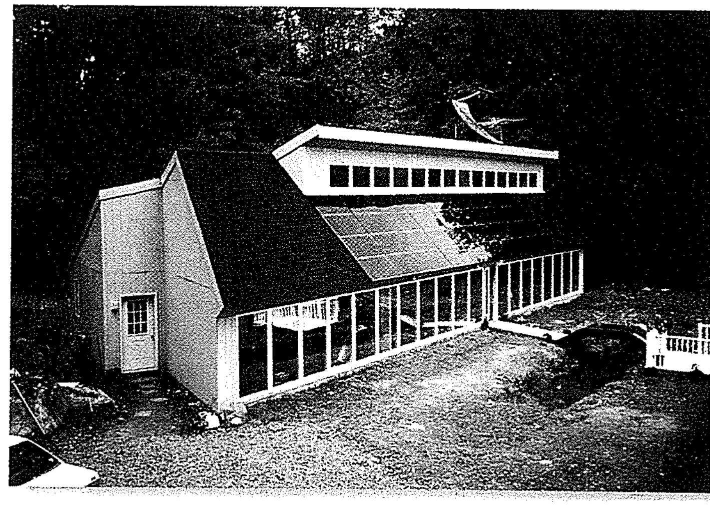


FIGURE 20.14 Roof-mounted solar panels (shiny area) can generate enough electricity for a house full of efficient appliances. On sunny days, this array can produce a surplus to sell back to the utility company, making it even more cost efficient.

During the last 25 years, the efficiency of energy capture by photovoltaic cells has increased from less than 1 percent of incident light to more than 15 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. Photovoltaic prices are now dropping about 7 percent per year. When they reach $1 per watt (perhaps by 2020) their electricity should be competative with nuclear or coal-fired plants.

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, a self-taught inventor from Detroit, these noncrystalline silicon semiconductors can be made into lightweight, paper-thin sheets that require much less material than conventional photovoltaic cells. They also are vastly cheaper to manufacture and can be made in a variety of shapes and sizes, permitting ingenious applications. Roof tiles with photovoltaic collectors layered on their surface already are available (fig. 20.14). Even flexible films can be coated with amorphous silicon collectors. Silicon collectors already are providing power to places where conventional power is unavailable, such as lighthouses, mountaintop microwave repeater stations, villages on remote islands, and ranches in the Australian outback.

You probably already use amorphous silicon photovoltaic cells. They are being built into light-powered calculators, watches, toys, photosensitive switches, and a variety of other consumer products. Japanese electronic companies presently lead in this field, having foreseen the opportunity for developing a market for photovoltaic cells. This market is already more than $100 million per year. Japanese companies now have home-roof arrays capable of providing all the electricity needed for a typical home at prices in some areas competitive with power purchased from a utility. And Shanghai, China, recently announced a plan to install photovoltaic collectors on 100,000 roofs. This is expected to generate 430 million kWh annually and replace 20,000 tons of coal per year.

The world market for solar energy is expected to grow rapidly in the near future, especially in remote places where conventional power isn't available. At least 2 billion people around the world now have no access to electricity. Most would like to have a modern power source if it were affordable. They may be able to enjoy the benefits of electrical power without the whole complex of power plants, transmission lines, air pollution, and utility companies.

Think about how solar power could affect your future energy independence. Imagine the benefits of being able to build a house anywhere and having a cheap, reliable, clean, quiet source of energy with no moving parts to wear out, no fuel to purchase, and little equipment to maintain. You could have all the energy you need without commercial utility wires or monthly energy bills. Coupled with modern telecommunications and information technology, an independent energy source would make it possible to live in the countryside and yet have many of the employment and entertainment opportunities and modern conveniences available in a metropolitan area.

Electrical energy is difficult and expensive to store

Storage is a problem for photovoltaic generation as well as other sources of electric power. Traditional lead-acid batteries are heavy and have low energy densities; that is, they can store only moderate amounts of energy per unit mass or volume. Acid from batteries is corrosive and lead from smelters or battery manufacturing is a serious health hazard for workers who handle these materials. A