Chapter 16

WATER, WIND, BIOMASS
AND GEOTHERMAL ENERGY

Adding renewable technologies to the menu of available energy choices can contribute to a growing economy – domestically, by spurring competition and innovation, and internationally, by contributing to the balance of trade through the export of new products and technologies. Renewable technologies represent an important opportunity, but not a panacea for the U.S. energy economy. Their long-term contribution is predicated on overcoming remaining technical and cost barriers, mainly through intensified R&D. [...] Wind, geothermal, and biomass energy systems already can make limited contributions to meeting base and intermediate electrical loads. However, additional technical progress is needed to reduce the costs and enhance the competitiveness of renewable electric options, particularly for base-load applications."

(*National Energy Strategy, Executive Summary*, 1991/1992)

The Administration's energy policy promotes the development and deployment of renewable energy resources and technologies in the United States and abroad. By helping to reduce costs and by stimulating market adoption of U.S. renewable energy technologies, energy policy can accelerate the environmental, economic, and security benefits of increased use of renewable resources.

(*Sustainable Energy Strategy*, 1995)

Having discussed fossil fuels and nuclear fission, we have covered more than 90% of the energy supply in both the U.S. and the world. By discussing nuclear breeder reactors and nuclear fusion, we have made the transition from depletable to nondepletable energy resources. Table 16-1 summarizes the remaining nondepletable energy resources. There are several points to be made on the basis of this information. The first one is made with the help of the simple calculation shown in Illustration 16-1.

TABLE 16-1

Quantities of energy (potentially) available from nondepletable energy sources

Type of Nondepletable Energy	kW/acre
Solar energy at ground level	720
All the winds on earth	43
U.S. hydroelectric power	0.2
U.S. geothermal energy	0.02
U.S. tides	0.02

Illustration 16-1. Express the annual consumption of energy in the U.S. in the same units of Table 16-1.

Solution.

As shown in Figure 5-3, the U.S. consumes about 90 quads of energy per year. We know that energy divided by time is power, so this gives us power units (for example, kilowatts). In order to obtain kilowatts per acre, we need to divide the power (90 quads/year) by the area of the U.S. (about $3.6\text{x}10^6$ square miles, or equivalent to a rectangle that is 3600 miles wide and 1000 miles high). Thus

$$\left(\frac{90\text{ quads}}{\text{year}}\right) =$$

$$\left(\frac{90\text{ quads}}{\text{year}}\right)\left(\frac{1\text{ year}}{8760\text{ h}}\right)\left(\frac{1\text{ h}}{3600\text{ s}}\right)\left(\frac{10^{15}\text{ BTU}}{1\text{ quad}}\right)\left(\frac{1.055\text{ kJ}}{1\text{ BTU}}\right)\left(\frac{1\text{ kW}}{1\ \frac{\text{kJ}}{\text{s}}}\right) =$$

$= 3.0\text{x}10^9$ kW, or per unit surface area

$$= \left(\frac{3.0\text{x}10^9\text{ kW}}{3.6\text{x}10^6\text{ sq.mi.}}\right)\left(\frac{1\text{ sq.mi.}}{2.56\text{ sq.km.}}\right)\left(\frac{4\text{x}10^{-3}\text{ sq.km.}}{1\text{ acre}}\right) = 1.3\text{ kW/acre}$$

It is clear that only solar energy and wind energy have the potential to satisfy the global energy needs of the U.S. and the world. The former is society's hope for the 21st century and it is discussed in detail in Chapter 17. The latter has some limitations that make it impractical on a global scale; both its virtues and problems are discussed in this chapter. The remaining nondepletable energy sources, while not likely to make a global impact on society's energy supply, have great potential in certain locations and are also discussed below.

Geothermal Energy

The interior of the Earth is in a molten state. The average temperature increase as one penetrates through the crust – through the mantle and toward the core (see Figure 16-1) – is about 30 °C/km. The crust and mantle consist of a variety of rocks which either undergo chemical reactions with each other and thus liberate some heat or contain radioactive isotopes whose decay liberates heat. The core (at about 4000 miles from the surface) is thought to be a molten alloy of iron and nickel; it may also be a solid due to the very high pressure. In any case, it is very hot (close to 200,000 °C). The heat associated with such a high temperature is conducted to the surface and from there it is radiated into space (see Figure 3-1). The total quantity of this geothermal energy (*geo*=earth) is estimated to be about 180 trillion kilowatthours per year. This is more than the total electricity consumed in the world. However, two difficult problems prevent us from exploiting this energy. The fact that the average temperature gradient is relatively small (30 °C/km) means that the efficiency of conversion of geothermal energy to electricity will be small. The expenditure of energy in the process of harnessing geothermal energy – for example, by drilling deep into the earth's mantle – may be very large, and it may be very difficult to surpass the breakeven point (remember Chapter 14 and similar problems with fusion energy).

Practical utilization of geothermal energy is limited to the so-called “hot spots,” or sources of ‘concentrated’ geothermal energy. The temperature gradient here is larger than 30 °C/km and one does not have to drill very deep to find these high-temperature regions. There are two important geothermal systems of current interest: geothermal wells and dry geothermal reservoirs (rocks).

Geothermal wells (also called hydrothermal systems) contain hot water or steam that either gushes out or is pumped to the surface and used either for space heating or for driving the turbines. A schematic representation of a geothermal power plant is given in Figure 16-2. In contrast to power plants that use fossil fuels or nuclear fission, it produces no pollution and the ‘fuel’ (water) is essentially free. Therefore, the low efficiencies achieved, due to the low temperature of the steam, can be tolerated.

The world's largest plant that produces electricity from geothermal energy (1650 MW) is located at The Geysers, near San Francisco in California. Smaller plants are in operation in Lardarello, Italy (400 MW), Cerro Prieto in Mexico (645 MW), Broadlands in New

Zealand (145 MW) and in the Philippines. Japan also has ambitious plans to develop geothermal energy. While still by far the largest in the world, the production of geothermal electricity in the U.S. has been decreasing in the 1990s after a rapid growth in the 1970s and 1980s (Figure 16-3). In contrast, world capacity is continuing to grow exponentially (Figure 16-4), with The Philippines, Mexico, Italy, New Zealand and Japan being the leaders. Today it is roughly equivalent to that of ten large fossil-fuel or nuclear plants.

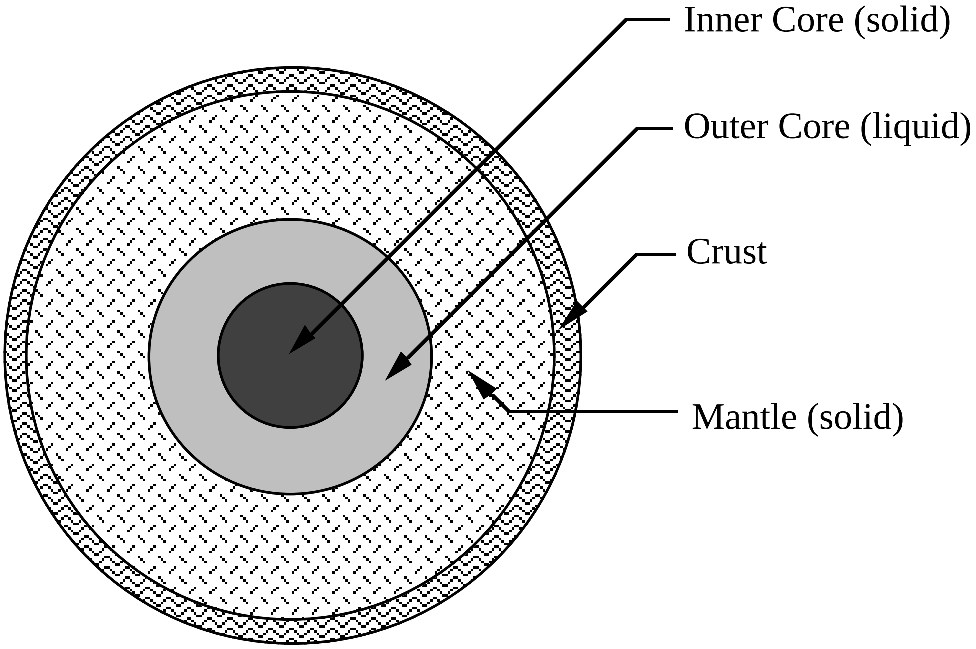

FIGURE 16-1. The Earth's crust, mantle and core (not drawn to scale).

Essentially all the geothermal resources in the U.S. are located west of the Mississippi river. Many of them are in environmentally protected areas, such as the Yellowstone National Park. Recent estimates by the Worldwatch Institute predict a modest role for geothermal energy in the world: 5 quads in 2025 and perhaps 10 quads in 2050.

One place where you would think geothermal energy makes sense is Hawaii. Indeed, Hawaii has recently been the site of much controversy over the development of geothermal energy and is a good example of the potential importance of geothermal energy on a local scale. Hawaii is heavily dependent on imported petroleum for electricity generation. The state government and several energy companies have plans to replace (by the year 2007) much of this imported oil with non-polluting geothermal energy. The plans call for the

FIGURE 16-2. Schematic representation of a geothermal electric power plant.

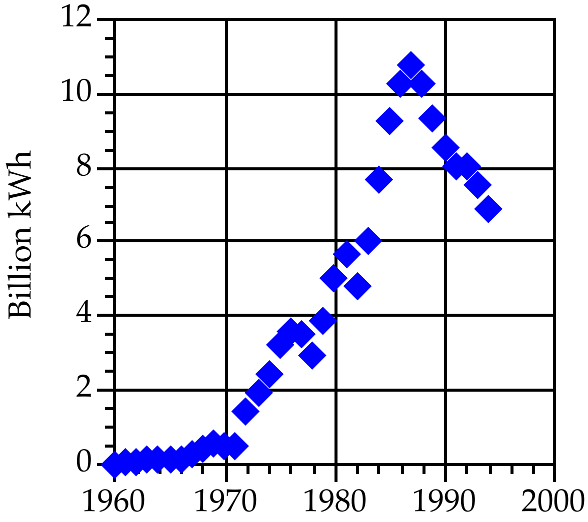

FIGURE 16-3. Generation of electricity in the U.S. using geothermal energy. [Source: Energy Information Administration.]

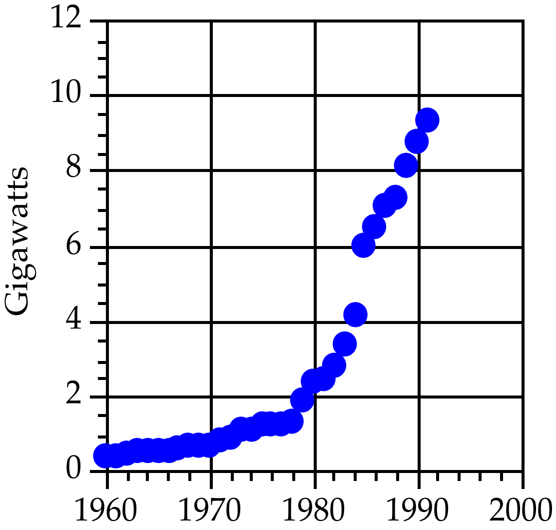

FIGURE 16-4
World geothermal electricity generating capacity. [Source: Worldwatch Institute.]

production of 500 MW of electricity on 142 acres of the Wao Kele O Puna rain forest. Molten underground rock abounds in this volcano-studded area, but the concern of environmental groups over the fate of some of the rain forest habitat may delay this project. (See *Time*, August 13, 1990, p. 68.)

Wind Energy

The energy of the wind can be viewed as 'secondary' or indirect solar energy. The winds are caused by the uneven heating of earth's atmosphere, with consequent differences in the atmospheric pressure at different locations. The familiar land-sea (onshore-offshore) breeze cycle is a good illustration of this phenomenon. During the day, the land heats to a greater extent than the nearby sea; as the air over the land is heated, it rises and is replaced by the breeze that brings air from the cooler sea. After sunset, the land cools faster than the sea; therefore, the now warmer air is over the sea and as it rises it is replaced by the breeze that brings air from the cooler land.

As we know from everyday experience, the daily wind patterns can be quite variable. But the monthly average speeds and directions of winds are surprisingly predictable and can be relied upon for conversion of their energy into more useful forms such as electricity.

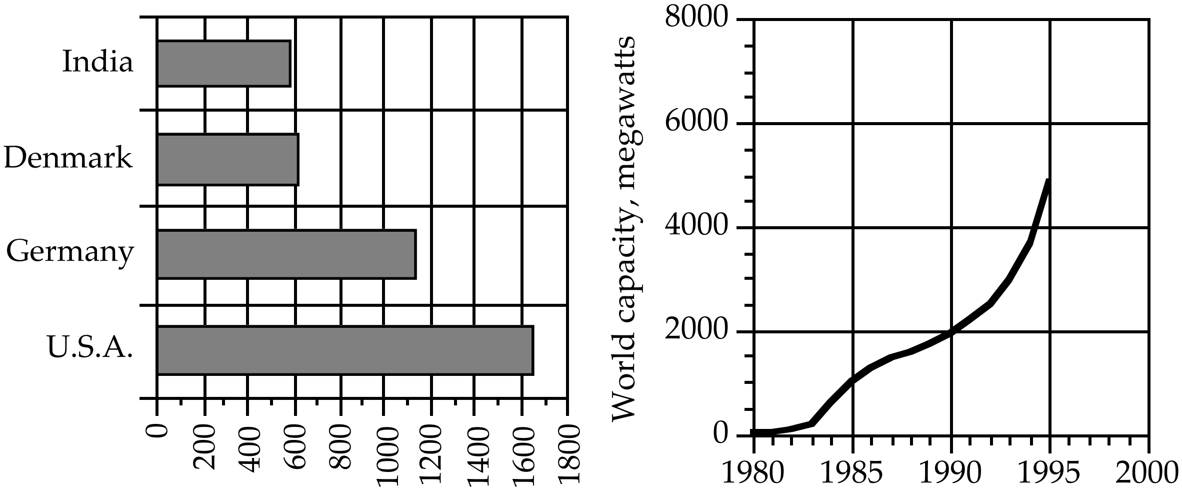

Figure 16-5. Trends and current status of wind-based electricity generation, in megawatts. [Source: *Vital Signs 1996*, Worldwatch Institute.]

The energy of the winds has been used for centuries to pump water for irrigation, to carry sailing ships across the oceans and to turn millstones to grind flour from grain. For centuries, windmills were a trademark of many European countries. In The Netherlands water needed to be pumped from the below-sea-level land; in Spain's Castille windmills were immortalized by Cervantes in *Don Quixote*. In the U.S., by the early 1900s, several million windmills were in use to pump water. In today's age of cheap and efficient electric motors, the revived interest in wind energy is focused exclusively on electricity generation.

Figure 16-5 summarizes the current capacity in the world and the leading nations. It is seen to be of the same order of magnitude as world's geothermal energy, though somewhat smaller. Europe remains the region of fastest growth of wind turbines, especially in the 1990s. After a period of fast growth in the 1980s (spurred by tax credits, which expired in 1985), the U.S. capacity hasn't changed much in the 1990s. California leads the way, as it does in most other energy-related initiatives. For example, 80 square miles of hills east of San Francisco (Altamont Pass) are already ‘decorated’ with 7000 wind turbines; another 4000 are spinning outside Palm Springs. The period of stagnation in the U.S. is expected to cease by the turn of the century; for example, a 400-MW plant was scheduled to be added at Buffalo Ridge, Minnesota by 2002. But it is very unlikely that optimistic predictions, such as 10% of the nation's electricity by the year 2000, will be realized. Wind industry's complaints about the lack of significant government support, in contrast to the situation in Europe, may be a problem.

INTERNET INFO	For the most recent developments in the wind energy industry, see the site of the American Wind Energy Association, at www.igc.apc.org/awea.

In addition to the obvious flexibility and reliability that are needed to respond to winds of variable speed, the key issue in the use of wind turbines is their efficiency. Conversion of the kinetic energy of the moving mass of air into the rotation of the blades – placed perpendicular to the direction of the wind – and subsequently into electricity can never be 100% efficient. (If it were, the wind would stop right there, at the blades.) The classic Dutch windmills had (and still have) an efficiency in the range of 5-10%. Modern wind turbines have maximum efficiencies in the range of 35-40%, and typical efficiencies in the range of 20-25%. The theoretical maximum is 60%. But, as in the case of geothermal energy, the ‘fuel’ for the power plant is free and relatively low efficiencies do not necessarily mean that the economics are unfavorable (see Chapters 17 and 18).

From Chapter 3, we know that the kinetic energy (of wind, for example) can be expressed as follows:

$$E_k = \frac{mv^2}{2} ,$$

where m is the mass of the air and v is its speed. Now, power (P) is energy divided by time (t), so the power of the wind will be:

$$P = \frac{mv^2}{2t} .$$

The mass (of air) is the product of the density (ρ) and volume (V); therefore, we have:

$$P = \frac{V\rho v^2}{2t} \ .$$

When the volume of air of interest is obtained by considering the diameter (d) of the windmill blades, the total power of the wind (at 100% conversion efficiency) is obtained as

$$P = \frac{\rho \ d^2 \ \pi \ v^3}{8} \ .$$

(No more than 60% of this wind energy can be converted into kinetic energy of the windmill blades.) It is seen to depend on the cube of the wind velocity and on the square of the blade diameter (d). This simple expression allows us to evaluate quantitatively the potential of wind turbines for generating electricity, as shown in Illustration 16-2.

Illustration 16-2. If the wind velocity is 10 miles per hour, and the turbine blades are 10 ft in diameter, calculate the maximum electric power that can be obtained.

Solution.
The density of air at atmospheric conditions (atmospheric pressure and about 20 °C) is about 1.3 kg/m^3. Thus we have:

$$P = (\frac{1}{8})\ (1.3\ \frac{\text{kg}}{\text{m}^3})\ (100\ \text{sq.ft.})\ (\frac{0.09\ \text{m}^2}{1\ \text{sq.ft.}})\ (3.14)\ (10\ \frac{\text{mi}}{\text{h}})^3\ (\frac{1600\ \text{m}}{1\ \text{mi}})^3\ (\frac{1\ \text{h}}{3600\ \text{s}})^3 =$$

$$= 403\ \frac{\frac{\text{kg m}^2}{\text{s}^2}}{\text{s}} \ = \ 403\ \frac{\text{J}}{\text{s}} \ = \ 403\ \text{W}$$

Assuming that the efficiency of conversion of the wind's energy to electricity is 25%, the electricity produced would be:

$$\text{Electricity} = [403\ \text{W (kinetic)}]\frac{[0.25\ \text{W (electric)}]}{[1\ \text{W (kinetic)}]} \ = \ 101\ \text{W (electric)}$$

This is equivalent to the consumption of one electric bulb (not much!). It can be shown easily that for a wind of 55 miles per hour, the maximum wind power (with the same blade size) would be 67 kW. (The world's largest windmill - with a horizontal axis - is in Oahu, Hawaii; its diameter is 320 feet.)

So wind energy is not going to make an impact on the energy supply/demand balance of a nation or the world any time soon. For example, the number shown for the U.S. in Figure 16-5 represents less than 0.5% of the total electricity capacity (see Chapter 18). It may be impractical to cover large portions of the earth's surface with tall wind turbines having long blades, even though the potential exists (see Figure 16-6), especially between the Rockies and the Mississippi river. The untapped potential of the Great Plains is a mixed blessing: on one hand, the land between the turbines could be used for farming; on the other hand, turbines located in the Dakotas, for example, would be far from large power consumers.

FIGURE 16-6. Potential for wind exploitation in the U. S. (numbers are in W/m^2).
[Source: Electric Power Research Institute]

Media reports in the past several years have been quite optimistic (see end-of-chapter Investigations). The U.S. manufacturers are offering today variable-speed turbines with rotor-blade diameters exceeding 30 meters and capacities as high as 500 kW (see, for example, the NYT of 11/18/93, “150 Windmills to Test Elusive Power Source”). Here is a quote from a typical letter to *The New York Times Magazine* (11/5/95): “North Dakota may be empty, but it's also home of the largest concentration of wind energy in the United States. If wind farms were put there, instead of wheat, it could supply about a third of the country's electric power – cleanly, sustainably and inexpensively. The building, installing and maintaining of wind turbines could support the state economy for the next 20 years.” Whether or not such optimism is misguided, as it appears to be, remains to be seen. It all depends on the cost of wind-generated electricity, of course, and dramatic progress has been made here in the last 15 years (see Chapters 17 and 18 and Investigation 16-8).

FIGURE 16-7. Harnessing tides. [From “Physics for Scientists and Engineers (with Modern Physics),” Second Edition. Copyright © 1986 by Saunders College Publishing. Reprinted by permission of the publisher.]

Some concerns have been raised about the deleterious environmental effects of wind farms (see, for example, *House Beautiful* of September 1992). Those typically mentioned are noise, unsightliness, threat to wildlife (e.g., birds). But there is no question that these are trivial issues in comparison with those of fossil-fuel-powered or nuclear power plants.

Tidal Energy

The well known phenomenon of tides is a consequence of the interaction of the gravitational and rotational forces of the sun, moon and earth. The ocean moves toward the moon (away from earth) on the side facing the moon. This results in the familiar up-and-down movement of water along the coast. How one can harness the tides is illustrated in Figure 16-7. The seawater is trapped with a dam in a bay at high tide (Figure 16-7a). During low tide, it is released from the bay to the ocean (Figure 16-7b). As it falls, it turns a turbine and the mechanical energy of the rotating turbine is converted into electricity (in an electric generator). As the high tide appears again, the ocean level rises and the water level in the bay is maintained low because the dam gate is closed (Figure 16-7c). When the gate is opened, water now falls from the ocean into the bay and electricity is produced (Figure 16-7d), and the new cycle begins (Figure 16-7e).

The only major tidal electric plant is in France, on the river Rance. It began operation in 1966 and produces 240 MW, with a yearly output of about 500 million kilowatthours. In the U.S. (and Canada), considerable potential exists in the Bay of Fundy, along the coast of Maine and on the Annapolis river (estimated at 15,000 MW of electricity), but no major plant is yet in operation there.

The principal problem of tidal energy is the relatively small difference in height between the two levels of water, during high tide and low tide (see Figure 16-7). This tidal range, or 'head', determines the maximum energy that can be obtained, because it is the gravitational energy of the falling water that is ultimately converted into electricity. Illustration 16-3 shows a typical calculation. The result obtained for the efficiency seems to be excessively large. Typical efficiencies of conversion of tidal energy into electricity are 10-25%. So one of the numbers in the above calculation must be wrong. If the plant is used only 3000 hours per year (instead of 8760), which makes more sense, the result is more reasonable. The reader is thus reminded that any calculation is valid only to the extent that the assumptions used – and there are many of these in any calculation – are valid as well.

Hydroelectric Energy

This is a form of energy that is also obtained by converting the gravitational energy of the falling water into electricity, but one that is much more important than tidal energy. Figure 16-8 shows the familiar water (hydrologic) cycle on which hydroelectricity is based.

Illustration 16-3. The average tidal range on the river Rance is 8.4 meters. It has been reported in the media that its tidal power plant provides about $3.1\text{x}10^9$ kWh per year (in the form of energy of the falling water). (a) How much water is used to produce this quantity of energy? (b) If the plant produces 240 MW(e), calculate its efficiency.

Solution.
(a)

$$m = \frac{E_p}{g\ h} = \frac{3.1\text{x}10^9\ \text{kWh}}{(10\ \frac{\text{m}}{\text{s}^2})(8.4\ \text{m})} \left(\frac{3.6\text{x}10^6\ \text{J}}{1\ \text{kWh}}\right) \left(\frac{1\ \frac{\text{kg m}^2}{\text{s}^2}}{1\ \text{J}}\right) = 1.3\text{x}10^{14}\ \text{kg (per year)}$$

(Compare this number with the number given for a hydroelectric power plant in Illustration 16-4.)

(b) $$\text{Efficiency} = \frac{\text{Useful energy output}}{\text{Energy input}} = \frac{240\ \text{MW}}{3.1\text{x}10^9\ \frac{\text{kWh}}{\text{year}}} \left(\frac{1000\ \text{kW}}{1\ \text{MW}}\right) \left(\frac{8760\ \text{h}}{1\ \text{year}}\right) = 68\%$$

FIGURE 16-8. The water cycle. [From “Energy and Problems of a Technical Society,” J.J. Kraushaar and R.A. Ristinen. © 1988 by Wiley. Reproduced with permission.]

Illustration 16-4. Calculate the potential energy of the falling water at the Hoover dam (Colorado river, Nevada), where $6.6\text{x}10^5$ kg of water per second fall over a distance of 221 meters. What is the efficiency of the plant if it can produce 1344 MW of electricity?

Solution.
The potential energy of the water is mgh, and since power is energy divided by time, the power of the falling water at the Hoover dam is obtained as:

$$P = \frac{m\ g\ h}{t} = (6.6\text{x}10^5\ \frac{\text{kg}}{\text{s}})\ (10\ \frac{\text{m}}{\text{s}^2})\ (221\ \text{m}) = 1.5\text{x}10^9 \frac{\frac{\text{kg m}^2}{\text{s}^2}}{\text{s}} = 1.5\text{x}10^9\ \frac{\text{J}}{\text{s}} = 1500\ \text{MW}$$

The efficiency of the plant is seen to be very high (about 90%), as expected.
Note from this calculation that the power is also proportional to the flow of water.

Water evaporates from the earth's surface when it is heated by sunlight, and eventually condenses in the atmosphere to form clouds. Rains bring it back to the surface and it can be stored in a reservoir, separated from a flowing river, lake or from sea level by a dam. The potential energy available for conversion to electricity (by falling onto a turbine/generator) is proportional to the height of the dam. The world's highest dam is Rogun, in the former U.S.S.R. (335 meters). In the United States, the highest dam (230 meters) is Oroville, on the Feather river in California. The largest hydroelectric power plant in the U.S. is the Grand Coulee, on the Columbia river in Washington, with a capacity of more than 6000 MW. It has a 168-meter dam that holds 11.8 billion cubic meters of water. The largest hydroelectric project in the world is at Itaipú, on the Paraná river between Paraguay and Brazil. The installed capacity of the plant is 12.6 GW. It supplies 85% of all the electricity consumed in Paraguay. (Talk about putting all the eggs in one basket! Norway does it too, with more than 90%...) There are plants that produce vast amounts of electricity even though they have a low head. For example, the Robert Moses plant on the St. Lawrence river has a capacity of 800 MW, even though its head is only 30 feet.

Hydroelectricity provides about 5% of world's energy supply, as illustrated in Figures 5-12 and 5-13. It provides almost 20% of the electricity consumed in industrialized nations and 30% of the electricity consumed in the less-developed countries. It accounts for less than 5% of the U.S. energy supply (see Figure 5-14). In the U.S., it produced about 260,000 gigawatthours of electricity in 1990, or some 10% of the total electricity generation (see Chapter 18). In many respects, it is the ideal source of electricity. In addition to being nondepletable, it is highly efficient (about 90%), because it involves the conversion of low-entropy energy forms (potential to mechanical and mechanical to electrical). It is clean, because it produces no pollution; there are no combustion products and no radioactivity is produced. It is reliable because, except for the turbine and the generator, there are no moving parts and little maintenance is needed. It is economical because of these low maintenance costs and because the ‘fuel’ (water) is essentially free; furthermore, there is no cost of waste disposal, because there is essentially no waste.

Worldwide, the amount of hydropower that could be exploited commercially is estimated to be about five times larger than that currently used. The hydroelectric potential of less developed countries is particularly large, estimated at about ten times the amount already in use. Unfortunately, it is not expected that hydroelectric energy supply will experience a substantial growth in the near future. The trends followed in the last two decades are shown in Figure 16-9. The characteristic exponential growth of energy and electricity production (see Chapters 5 and 18) is not observed. Many of the potentially interesting resources may remain undeveloped either because of environmental preservation (particularly in the United States) or because they are not economical.

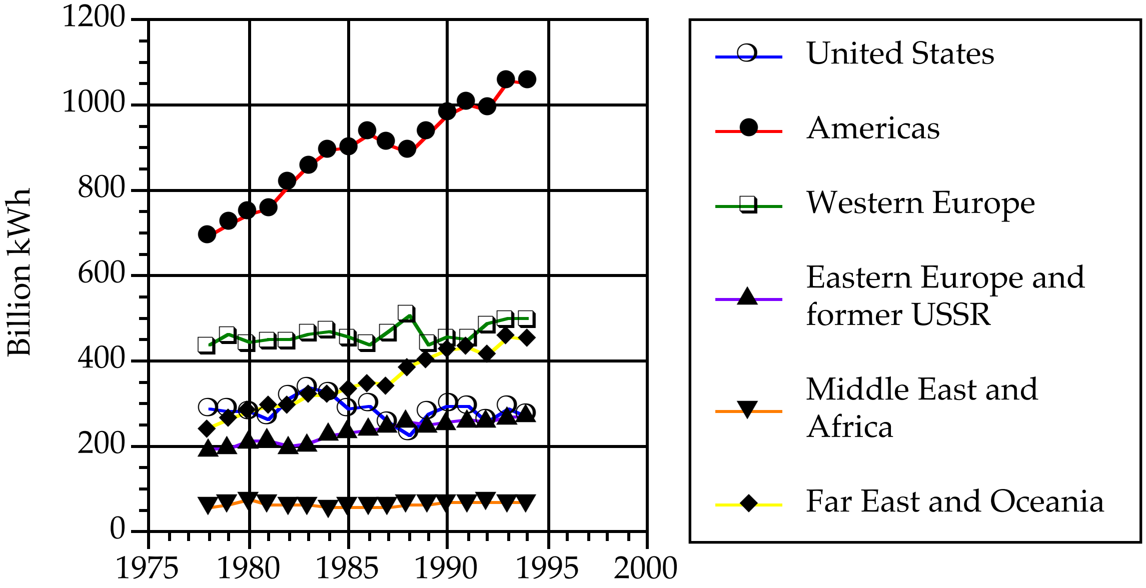

FIGURE 16-9. Hydroelectric energy production in the world.
[Source: Energy Information Administration.]

Wave Energy

When wind blows across the ocean it creates waves. Temperature differences caused by uneven heating of the ocean also contribute to the formation of waves. Wave energy is, therefore, also secondary (or tertiary!?) solar energy. Development of wave energy is in its infancy, when compared to the other renewable energy forms discussed elsewhere in this chapter. Nevertheless, there have been recent attempts to construct ‘seamills’ and thus obtain power from the ocean, particularly in remote locations and on islands. For example, Norway has a 850-kW plant (enough for a community of 8000) at Tostestallen, on the Atlantic coast (*The New York Times*, February 10, 1987, p. C1). On the island of Islay, in Scotland, the construction of a 40-kW pilot plant has been announced recently (*The New York Times*, September 25, 1990, p. C1). The biggest wave energy power plants (1.5 MW each) are in Australia and the on the Indonesian island of Java (*The Los Angeles Times*, June 28, 1991, p. D1).

Biomass Energy

In Chapters 2 and 6 we mentioned the process of photosynthesis, which is responsible for life on earth and is part of the carbon cycle. It is this process that produces *biomass*, which is a generic term for the vegetable material obtained from sunlight, water and carbon dioxide. Instead of waiting – many millions of years – for the biomass to concentrate its energy by decay into fossil fuels (see Chapter 6), and only then use it, there is the possibility of using this nondepletable energy form directly, mostly by burning it. In fact, this is how we humans survive (at least in part): the energy required for our metabolic processes is supplied by burning the plant-derived food that we eat.

For centuries society has relied on one form of biomass, wood, to satisfy most of its energy needs. This was illustrated in Figure 6-3. Wood, and biomass in general, represents today only a small fraction of energy consumption in the U.S. This is shown in Figures 5-14 and 16-10. In the less developed countries, however, wood is an important energy source, especially for residential consumption. This was shown in Figure 5-13, under “other sources” which represent 13% of the overall energy consumption.

One of the problems with the use of biomass energy is the relatively low energy density of these fuels, in comparison with fossil fuels. Some of the representative heating values and other relevant properties of agricultural waste, municipal solid waste and wood are given in Table 16-2. This list of candidates for biomass energy production is far from being complete. Any fast-growing plant can be used. (In 1990 the Associated Press carried a report that even marijuana is being considered as an energy source, by no other than the Ministry of Energy of New South Wales, Australia.) These numbers should be compared with the carbon content of coals of 60-90% and typical heating values of coals of 25,000-35,000 kJ/kg (10,000-15,000 BTU/lb).

Given the increasing costs and space limitations associated with the storage of waste (especially municipal waste), it had been expected that the use of garbage as biomass fuel would increase. This seemed like a perfect candidate for killing two birds with one stone because the other two alternatives to the garbage problem, transportation and recycling, have had only limited success (see “The Garbage Problem: It May Be Politics, Not Nature” in NYT of 2/26/91). However, Figures 16-11 and 16-12 show that the early optimism for waste-to-energy incineration seems to be fading (see, for example, the NYT of 3/13/96, “Embattled L.I. Incinerator To Go Way of Shoreham”).

TABLE 16-2
Selected properties of typical biomass fuels

Material	% Carbon	% Sulfur	% Ash	Heating Value (kJ/kg)
Bagasse (sugar cane refuse)	47.3	0.0	11.3	21,255
Feedlot manure	42.7	0.3	17.8	17,160
Municipal solid waste-general	34	0.4	38	13,000
Garbage	45	0.5	16	19,730
Newspapers	49.1	0.2	1.5	19,720
Beech wood (typical hardwood)	51.6	0.0	0.6	20,370
Pine (typical softwood)	52.6	0.0	0.2	21,280
Grass	48.4	0.3	1.7	18,520

[Source: A.W. Culp, “Principles of Energy Conversion,” McGraw-Hill, 1991.]

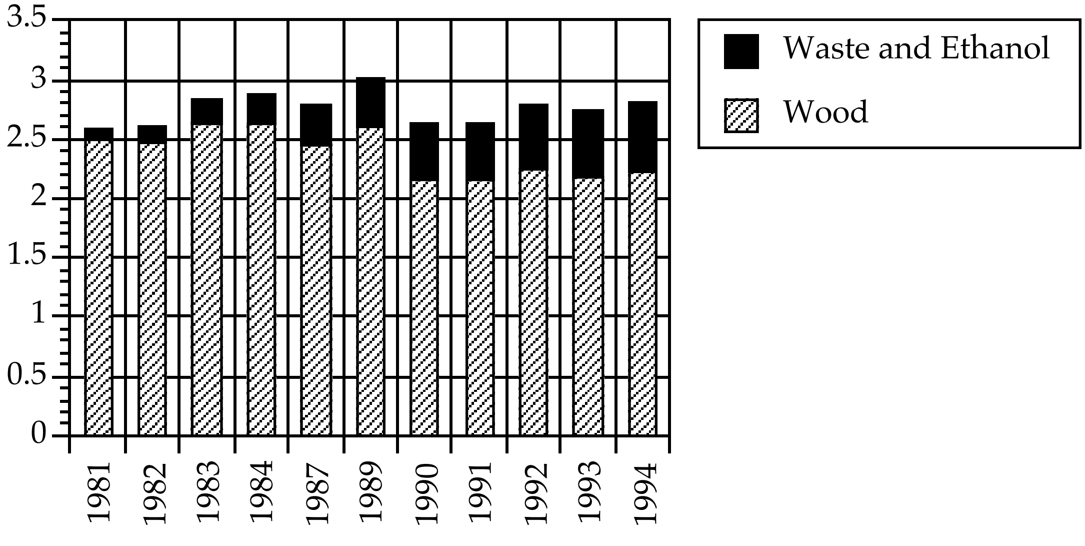

FIGURE 16-10. U. S. consumption of biomass energy resources (in trillion BTU). [Source: Energy Information Administration.]

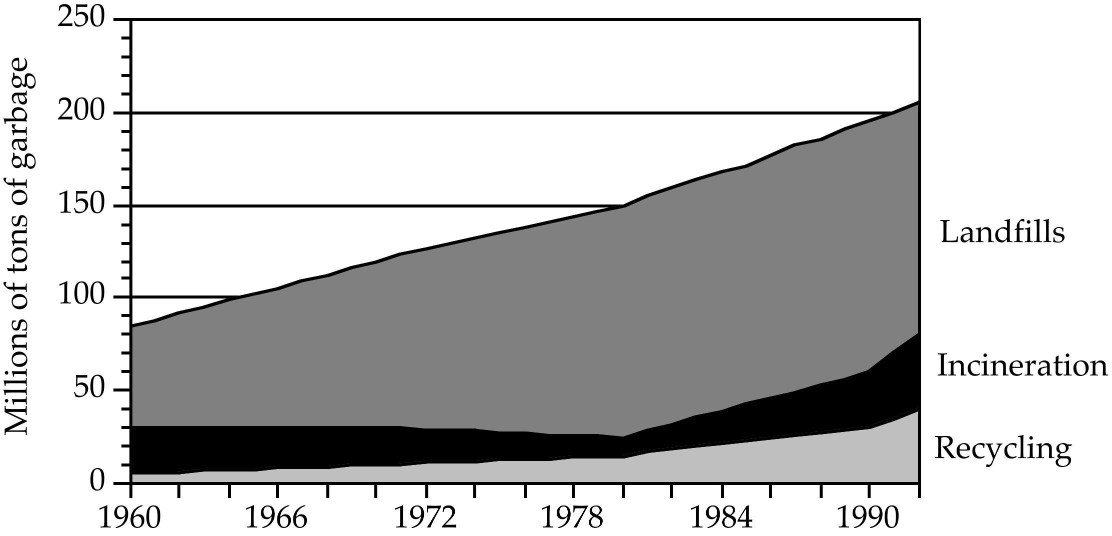

FIGURE 16-11. Accumulation of waste in the United States.
[Source: NYT of 10/11/94, "Burning Trash for Energy: Is It an Endangered Industry?"]

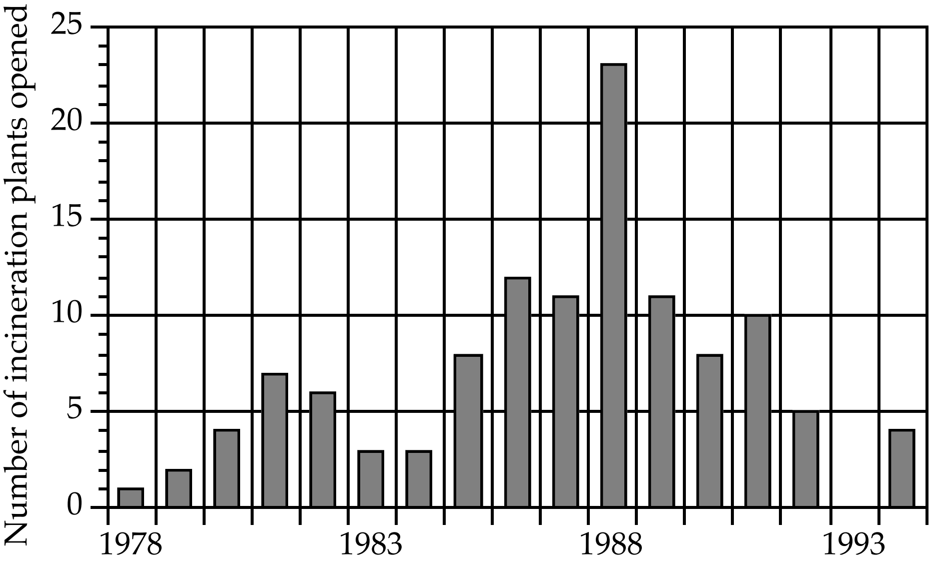

FIGURE 16-12. Statistics of incineration plant openings in the recent past.
[Source: NYT of 10/11/94, "Burning Trash for Energy: Is It an Endangered Industry?"]

An alternative approach to the use of biomass energy is the conversion of primary biomass (corn grain, for example) into a gaseous or liquid fuel that has a higher energy density. Methane, the ideal fuel in many respects (see Chapter 9) can be produced from biomass by anaerobic fermentation. In fact, this process occurs spontaneously in landfills. Methanol (or methyl alcohol with a heating value of 8500 BTU/lb) can be produced not only from natural gas (Chapter 9) or coal (Chapter 7) but also from wood or municipal solid waste. *Gasohol* is another fuel that has attracted plenty of attention recently. It could replace gasoline in automobiles. It is a mixture of grain-derived ethanol (or ethyl alcohol with a heating value of 12,000 BTU/lb) – typically as a 10-15% additive – and gasoline. Ethanol can be produced from corn (or any other grain) by fermentation, just as wine is obtained from grapes and beer from cereals. A great deal of energy is expended, however, to grow the grain and produce the ethanol in the first place. So there is some debate among scientists, economists and politicians about the feasibility of reaching a breakeven point in the overall process. A simple-minded economic analysis is straightforward: it costs more to produce a gallon of ethanol (say, $1.40) than a gallon of gasoline (around $0.50). But the advantages of ethanol with regard to the trade deficit, air pollution and even national security may make the comparison less unfavorable. Brazil, whose climate is well suited for sugarcane agriculture, has been using both gasohol and pure ethanol in its automobiles (see Chapter 20) since the 1970s, with mixed results.

Recent media reports reflect special interest in ethanol. You may have seen the TV commercials by Archer Daniels Midland (ADM), which advocate the use of ethanol in automobiles to minimize smog. The following excerpt from a letter to the NYT (9/9/96) is typical: “We Americans cannot have it both ways. Either suffer with our dependence on the Middle East and enjoy the smog, or support the ethanol industry.” You may also have seen the Mobil advertisements which, not unpredictably (see Chapter 20), are not enthusiastic about ethanol. After all, gasoline is made from oil, and that's Mobil's business. But if you need votes from grain-growing farmers – as President Bush needed them in the 1992 campaign – or if you own ADM stock, you would also probably support ethanol.

The undeniable attraction of biomass energy is that it would not contribute to the greenhouse effect (see Chapter 11). This is illustrated in Figure 16-11. Whether used directly in power plants or indirectly (to produce alcohol fuel for automobiles), the amount of carbon dioxide released would be balanced by the amount of carbon dioxide consumed during photosynthesis. This argument assumes that tree plantation and growth (biomass production) can keep up the pace with society's ever-increasing appetite for more energy and more electricity (see Chapter 5). Table 16-3 shows the production rates for representative biomass fuel candidates in different parts of the world. It is seen that tropical zones have the maximum productivity. It is not surprising, therefore, that the largest ethanol production activity, based on sugarcane, is in Brazil, where much of the imported oil is being replaced by gasohol.

FIGURE 16-13. Schematic representation of an ideal biomass cycle.

Illustration 16-5. Calculate how much area of a sugarcane plantation is needed to produce 90 quads of energy.

Solution.
Let us assume that the sugarcane is burned directly, with a heating value of 5000 BTU/lb. To produce $90\text{x}10^{15}$ BTUs of energy, we need:

$$\frac{90\text{x}10^{15}\ \text{BTU}}{5000\ \dfrac{\text{BTU}}{\text{lb}}} = 1.8\text{x}10^{13}\ \text{lb of sugarcane} = 8.1\text{x}10^{15}\ \text{g of sugarcane}$$

The plantation required would thus have the following characteristics:

$$\frac{7.3\text{x}10^{15}\ \text{g}}{7500\ \dfrac{\text{g}}{\text{m}^2\ \text{year}}} = 1.1\text{x}10^{12}\ \text{m}^2\ \text{year}$$

In one year, this would require an area of $1.1\text{x}10^{12}$ m^2; in half a year, it would require twice that amount ($2.2\text{x}10^{12}$ m^2); etc. So a sugarcane plantation area of about a million square kilometers (one thousand km long and one thousand km wide) would be necessary to satisfy the needs of the U.S. population (some 90 quads per year).

TABLE 16-3

Net biomass production rates for natural and agricultural ecosystems

Natural/Agricultural Ecosystem	Production (g/m^2/year)
Beech forest (Denmark) - temperate zone	1,450
Tropical forest (Ivory Coast) - tropical zone	1,340
Sewage ponds (California) - freshwater	5,600
Algae on coral reef (Marshall Islands) - marine water	4,900
Corn (U.S. average) - temperate zone	2,500-4,000
Sugarcane (Hawaii) - tropical zone	7,200-7,800
Sugarcane (Java) - tropical zone	9,400

REVIEW QUESTIONS

16-1. Show that the 180 trillion kilowatthours of geothermal energy, mentioned on p. 293, is in reasonable agreement with the number given in Table 16-1. Also check the numbers given by David Tenenbaum in *Earth* magazine of 1/94: “Every year the planet bleeds about half a trillion calories of its internal heat per square mile into the oceans and atmosphere.”

16-2. In 1994 U.S. geothermal energy sources generated some 7 billion kWh of electricity (Figure 16-3). How many conventional 1000-MW power plants are needed to produce this much electricity if they operate 7000 hours per year?

16-3. Hurricane Fran hit the coasts of the Carolinas with winds of 120 miles per hour. If these winds could be harnessed using turbines with 10-meter blades at 60% efficiency, how many turbines are needed to generate 500 megawatts of electricity? If the wind speed is 20 miles per hour, how many more turbines would be needed?

16-4. If the wind potential in Texas is 600 W/m^2, how much land is needed for a 500-MW electric power plant?

16-5. The NYT of 2/14/89 has a report on an unconventional way to produce electricity from biomass (“Cow Manure Fuels a California Power Plant”). The plant produces 15 megawatts of electricity, “enough for 15,000-20,000 homes, using 800 to 900 tons of [cow] manure daily.” If the efficiency of the plant is 30%, calculate the heating value of this biomass fuel and compare it with the values provided in Table 16-2.

16-6. Indicate whether the following statements are true or false:
(a) The most attractive locations for installing wind turbines in the U.S. are in the southeastern part of the country,
(b) It is expected that, over the next few decades, there will be a significant increase in the number of hydroelectric power plants in the U.S.

(c) It is expected that, over the next few decades, there will be a significant increase in the number of wind turbines in the U.S.
(d) Figure 16-3 shows that in 1990 the U.S. generated less than 20% of the world's geothermally produced electricity (assuming these power plants operated 6000 hours/yr).
(e) From Figures 16-10 and 5-14 it is concluded that biomass energy contributed much less than 0.1% of the total energy consumed in the U.S. in 1994.

16-7. Describe the two alternatives for biomass utilization which do not lead to accumulation of carbon dioxide in the atmosphere.

INVESTIGATIONS

16-1. Recent efforts in exploiting geothermal energy have been focusing on hot dry rock (HDR) reservoirs. In an article entitled “Mining Deep Underground for Energy ” (NYT of 11/3/91), Matthew Wald argues that “hot, dry rock may be the nations biggest potential power source.” Summarize the virtues and liabilities of this geothermal resource.

16-2. In *Earth* magazine of January 1994 (“Deep Heat: The Uncertain Promise of Geothermal Power”), David Tenenbaum writes that “the United States alone contains energy equivalent to 2,000 trillion barrels of oil in its hot dry rocks – roughly 125,000 times the energy Americans consume each year.” (a) Are these numbers right? (b) Summarize his arguments in favor of (and against?) this “inexhaustible supply” of energy.

16-3. Find out more about the status of the “world's largest geothermal power company,” created by a merger of Magma Power Company and California Energy Company. See, for example, NYT of 10/5/94 and 12/6/94. Check the World Wide Web as well.

16-4. According to Madrid's *El País* of 5/10/94, the 30 MW plant at Tarifa, in southern Spain, is the most productive wind power plant in the world. It has 250 turbines which were in operation for 2600 hours in 1993. Find out the productivity of California's wind turbines and compare it with that of Tarifa's wind farm. See *National Geographic* of 10/93 and the NYT of 5/22/88 (“The Promise of Wind Awaits a New Energy Crisis”).

16-5. In the NYT of 4/11/95 (“70's Dreams, 90's Realities. Renewable Energy: A Luxury Now. A Necessity Later?”) Agis Salpukas writes: “Kenetech [a leader in the wind turbine business] got commitments in recent years from the state's three largest utilities to buy up to 945 megawatts of power – enough to run a city the size of Phoenix and the biggest order for wind power ever. It meant supplying 2,800 turbines, worth about $1 billion.” Estimate the capacity of each turbine. Check the status of this project and Kenetech's situation today. See the NYT of 12/27/95 and *World Watch*, 9-10/96. Also, visit the Web site of the American Wind Energy Association at http://www.igc.apc.org/awea.

16-6. In the NYT of 4/12/94, Matthew Wald has an article entitled “Cheap Electricity Stalls Wind Power as an Energy Source.” Summarize its main arguments.

16-7. *Time* magazine of 1/13/92 has an article with the following title: “Breezing into the Future.” How can America curb its dangerous dependence on scarce, nasty fossil fuels? The answer, my friend, is blowing in the wind.” Summarize its main points and compare them with those of the NYT article of 11/14/91 entitled “Putting Windmills Where It's Windy.”

16-8. In the NYT of 5/18/93, Richard Ringer discusses wind energy in an article entitled “Giving Wind Power a Better Image.” He quotes the following statement from a representative of the Union of Concerned Scientists (a lobby for renewable energy sources): “The cost of producing wind power is less than 6 cents a kilowatt.” What is wrong with this statement? Check also *Time* of 1/13/92. (Hint: Remember the important statement in Chapter 2: We buy power but we pay for energy!)

16-9. The NYT has published an article on wind energy entitled “A New Era for Windmill Power.” Its content reveals that it dates from the time when “U.S. Windpower [was] the only American company that builds windmills” and when the Altamont Pass facility was just starting up. Find out the exact date when this article appeared in press.

16-10. Find out the most recent information about the economics of wind energy. Certainly do explore the World Wide Web, but start with the WSJ of 9/6/91 (“‘Wind Farms’ May Energize the Midwest”). See also Chapters 17 and 18.

16-11. In a 1994 advertisement entitled “They're baaack...” in *Time* magazine, Mobil claims that ethanol derived from biomass (corn, for example) is not a renewable energy source. Find this ad and summarize the arguments that Mobil uses to support its claims.

16-12. In discussing the future of biomass energy, Flavin and Lenssen (see Further Reading, p. 461) say the following: “Biomass will first have to be converted to a liquid or gaseous fuel, or to electricity. The latter currently has greater economic appeal: electricity priced at 5 cents a kilowatt-hour is equivalent to oil at roughly $85 a barrel.” (a) Show that this equivalence is indeed correct. (b) Search the Internet (using keywords biomass *and* electricity) to get a sense of how popular this energy option may be.

16-13. In *Vital Signs 1993*, published by the The Worldwatch Institute, information is provided about the growth of hydroelectric capacity in the world since 1950. Make a graph that shows this trend and compare it with the information in Figure 16-9. Where is most of this growth taking place? Has the rate of growth increased or decreased in the period 1980-1995 in comparison with 1965-1980? Assume an average capacity utilization factor of 75%, or 6570 hours per year of actual electricity production.

16-14. Landfill methane (see Chapter 9) can be a renewable energy source, as long as we keep supplying the garbage to the landfills. And we have been very good at that lately (see Figure 16-11). Read *USA Today* of 12/26/96 (“‘Pretty cool’ idea will heat Missouri school”) to find out how some high-school students plan to exploit this alternative energy.