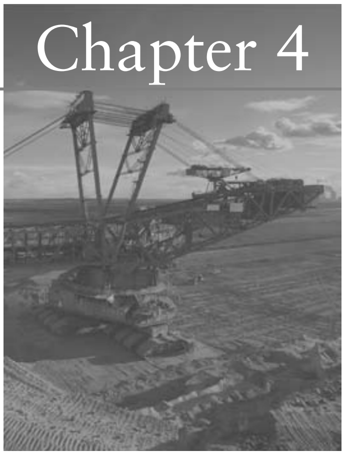
Chapter 4



Alternative Energy Resources

Useable energy from any source other than fossil fuels and nuclear energy is usually designated as alternative energy. This energy is typically from a renewable source and includes solar, wind, water, geothermal, and biological sources as given in **Figure 4.1**. Interestingly, the most populous country, China, is presently the number one investor in alternative energy. While solar, wind, tidal, and geothermal energy resources are virtually unlimited, each type has locations where its rate of production is highest and therefore makes the most sense to employ. The largest components of alternative energy resources used, biomass and hydroelectric energy that depend on farmable land area, and the extent of river flow, respectively, are starting to reach their production limits in most areas.

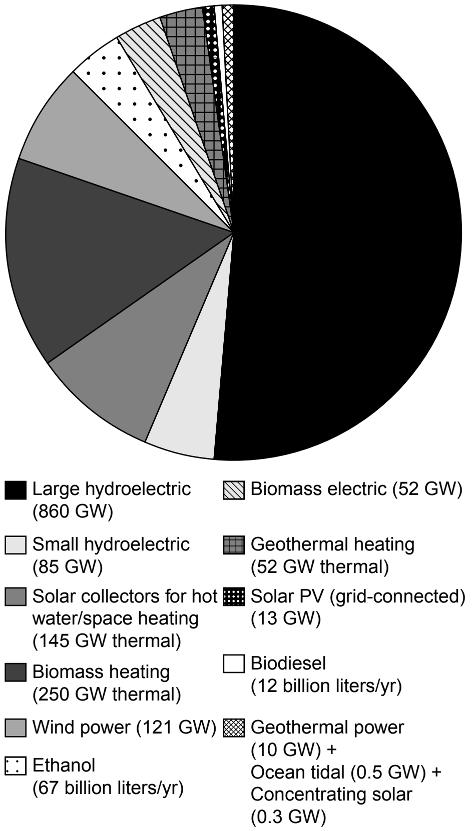


Figure 4.1 Global renewable energy capacity existing at the end of 2011. GW = gigawatts = 10^9 watts and "thermal" indicates heat energy not used to produce electricity. (Data from: *Renewables Global Status Report*, 2012.)

Solar Energy

Solar energy is energy from a whole spectrum of different wavelengths from short wavelength *ultraviolet radiation* to long wavelength *infrared radiation* from the sun. This is shown in **Figure 4.2** as light energy per unit area per unit wavelength interval. Note that the species, O_3, H_2O, and CO_2 in the atmosphere absorb parts of the spectrum from the sun transforming it into longer wavelength infrared (heat) energy before it reaches the surface. This infrared energy plus the infrared energy radiated back to space from the earth's surface causes the warming of the earth's atmosphere in what is termed the *greenhouse effect*. Like a greenhouse the shorter wavelengths of visible light from the sun pass through the transparent atmosphere. They are

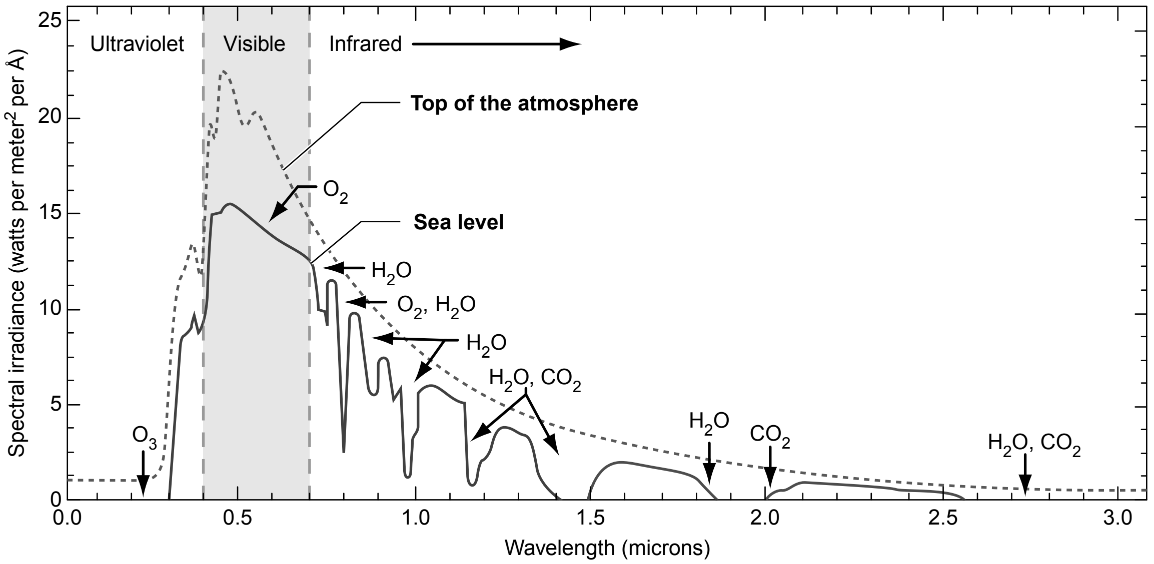


Figure 4.2 Spectrum of solar energy at the top of the earth's atmosphere (dashed line) and at sea level (solid line) indicating the dominance of visible light wavelengths. The arrows indicate absorption in the atmosphere of particular wavelengths by the indicated species. The grey area gives the part of the solar spectrum that can be seen with the human eye.

absorbed by the earth's surface producing longer wavelength infrared energy. This infrared energy warms the atmosphere.

Solar energy is the earth's most available energy source and has been used since prehistorical times. In terms of direct usage it can be divided into low-quality solar energy, which uses sunlight to change temperature, and solar power, which uses a sunlight concentrator to produce electricity or to activate a chemical process. The difference between solar energy and *solar power* is that energy is an amount given in an energy unit like joules and power is the rate that the amount of energy is produced or used given in a unit like watts. Typical units of measure for energy and power are given in **Table 4.1**. If considering energy usage over time often the units kilowatt-hr (kWh) or kilowatt-yr (kWyr) are used.

Low-Quality Solar Energy

The low-quality solar energy of direct sunlight is used primarily for space and water heating, clothes and food drying, cooking, and natural illumination in buildings. For instance, visible light passes through window glass and is converted into infrared energy when it encounters an object in the room. How much the room heats up and stays warm at night or on a cloudy day depends on the heat capacity of the objects in the room and the amount of heat that is transported out of the room. Energy can be transferred by three different mechanisms.

Radiation is the way heat or light is transferred through space as waves from a heated or lit object. It is how we obtain light energy from the sun. Standing in front of a fire the infrared radiation can be felt and the visible light radiation that reaches your eyes is observed. An object radiates a spectrum of wavelengths of energy with the wavelengths of the radiation shortening with increased temperature. Because the sun is hotter than a fire it produces shorter wavelength ultraviolet radiation as well as visible light. A human body, which is much cooler than a fire, radiates only longer wavelength infrared energy.

Moving a heated mass of material from one place to another also transfers energy. This is termed *energy convection*. Humankind uses the convection of hot water through pipes to carry heat from a furnace to

Table 4.1 ENERGY AND POWER CONVERSION FACTORS*

ENERGY = FORCE × DISTANCE OR PRESSURE × VOLUME

ENERGY UNIT	ERG	JOULE	THERMOCHEMICAL CALORIE	BTU
CGS: 1 erg = dyne cm =	1	10^{-7}	2.38901×10^{-8}	9.4782×10^{-11}
S.I.: 1 joule = newton meter =	10^{7}	1	0.23901	9.4782×10^{-4}
1 calorie =	4.194×10^{7}	4.1840	1	3.9657×10^{-3}
1 Btu = British thermal unit =	1.055056×10^{10}	1.055.056	252.164	1
1 kilowatt hour =	3.600×10^{13}	3.600×10^{7}	8.6042×10^{5}	3,412.1

POWER = ENERGY PER UNIT TIME

POWER UNIT	WATT	BTU HOUR^{-1}	HORSEPOWER (ELECTRICAL)	TON (REFRIGERATION)
1 watt = joule s^{-1} **=**	1	3.41443	1.340×10^{-3}	2.8435×10^{-4}
Btu hour =	0.292875	1	3.9259×10^{-4}	8.3278×10^{-5}
Horsepower (electrical) =	746.00	2,547.2	1	0.21212
Ton (refrigeration)† =	3,516.9	12,000	4.7143	1

System	Force Unit
CGS	dyne = force to accelerate a mass of 1 g by 1 cm s^{-2}
S.I. (MKS)	newton = force to accelerate a mass of 1 kg by 1 m s^{-2}

Force = mass × acceleration

*The most widely used systems of measurements are S.I. and CGS units. Given in this table are conversion factors between the two systems and some other common energy and power units.

†Ton of refrigeration is approximately the energy removal rate that will freeze 2,000 lb of water at 0°C in 24 hours.

warm a room in a house with a radiator. Hot air can be convected from one room to another by a forced-air heating unit. On the earth natural convection transfers heat by air masses in the atmosphere and seawater in the ocean from warmer equatorial regions towards cooler polar regions.

The third kind of heat transfer is by *conduction*. In conduction the transfer of energy from a hotter object to a cooler one is by collisions of neighboring atoms and free electron exchange. The free electron exchange explains why metals heat up much more rapidly than silicate rocks. Metals have clouds of electrons that transfer the heat. In contrast to convection in conduction the energy is transferred but there is no net motion of matter. Heat from a warm room can be conducted outside through a wall given enough time. In the earth heat from the interior is conducted outward to the surface through rocks. Understanding the mechanisms of heat transfer allows better use of solar energy, particularly for low quality purposes.

Solar Water Heating

Heating water by sunlight is a widely used technology, particularly in China with 40% of the world's capacity; it is also heavily used in Europe, Japan, and India. It is growing at almost 20% per year as an increasing number of countries, states, and cities are mandating solar hot water systems in new building construction. Most of this is for domestic usage but solar hot water also has industrial applications. Over 70 million households worldwide used solar hot water systems in 2011 with 27 million rooftop solar water heaters in operation in China alone. This supplies the energy equivalency of over 100 large nuclear power plants. In Rizhao and Dezhou, China, 99% of households in the city center use solar hot water heaters. In 2011, Worldwatch Institute estimated that 2 million Germans are living in homes where both water and interior space are heated by rooftop solar collectors.

To heat water with sunlight a solar collector is installed in a location with as much of an unobstructed view of the sun as possible, typically on a roof. It can be a thin box or set of tubes filled with water that are painted black for maximum energy absorption. The hot water is stored in a tank if hot water is used directly or run through pipes to a heat exchanger for space heating (**Figure** 4.3).

Turbines and Electrical Generators

Energy can be transported by electrons under a voltage. The force of water, steam, or air can be used to generate this voltage. What is required is a *turbine* and electrical *generator*. A turbine uses a stream of gas or liquid generated from heated water, water stored behind a dam, or wind to push against blades to rotate a shaft. Inside the generator electrical wire has been wrapped around the shaft. Rotating these wires in a magnetic field produces electricity. An electrical generator then converts the mechanical energy of the turning shaft into voltage that allows electrical energy to flow in a conductor as shown for a steam turbine and generator in **Figure** 4.4. This occurs because if one moves a wire through a magnetic field an electric current is produced. It can be thought of as a "reverse" motor as the generator converts the rotation of a shaft into electricity.

Solar Power

The possibilities for solar power production are different depending on where you are. For instance

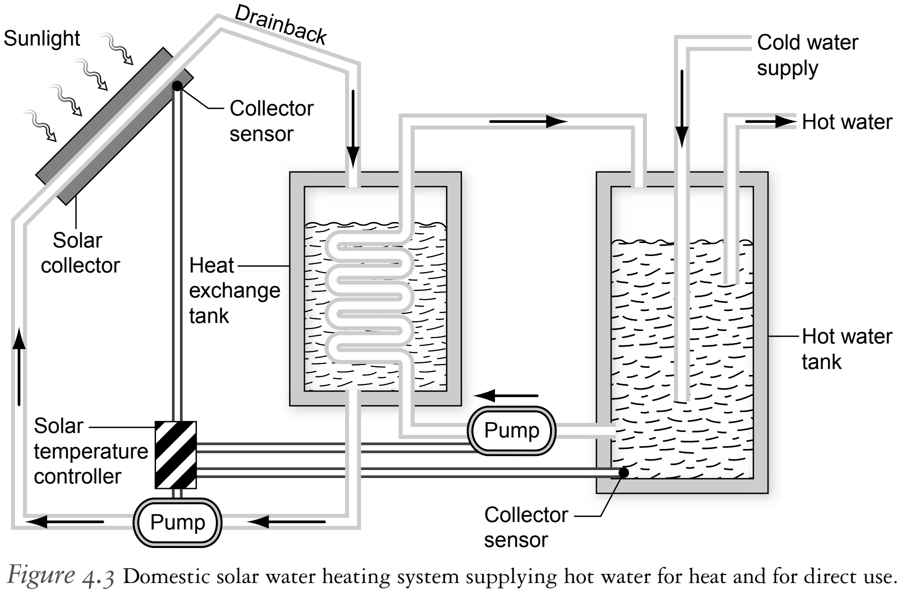


Figure 4.3 Domestic solar water heating system supplying hot water for heat and for direct use.

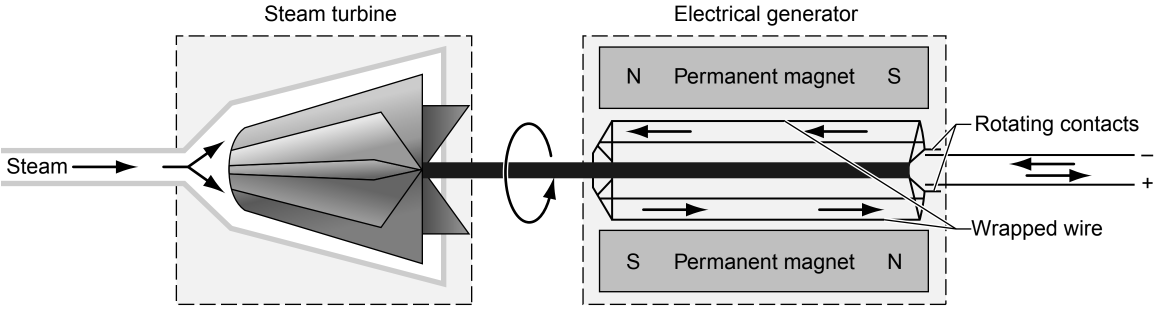


Figure 4.4 Steam turbine and electrical generator where the energy of the moving steam rotates a shaft with wires attached in a magnetic field to produce electricity.

the southwestern U.S. gets about twice the radiation from the sun of the eastern U.S. There are three ways to use the power. One way is to focus light from the sun with mirrors and lenses to heat a solar furnace. The heat can then be used to produce steam to power a turbine that runs a generator and produce electricity. A second way is to focus sunlight to provide the energy needed to run a chemical reaction; for instance, the splitting of water into H_2 and O_2. The H_2 produced can then be used as a fuel, similar to natural gas. Another use of this type is to generate heat from focused sunlight to drive industrial chemical reactions that require elevated temperatures. The third type of solar power usage is to produce an electric current in a *photovoltaic* (PV) *cell* as outlined below.

Solar Furnace Electricity

One type of solar furnace is a solar power tower, also known as a "central tower" power plant or *heliostat* power plant. It uses a tower to receive focused sunlight and an array of flat, movable mirrors called heliostats to focus the sun's rays on the collector tower to heat water or another liquid. The heated liquid is transformed to a gas to power a turbine and run a generator. Recent designs have used molten salt in place of water. Molten salt has a higher ability to store heat, that is, heat capacity. This heat is then transferred to water to produce the needed steam. Because heat can be stored in molten salt, electricity can be generated at night.

The THEMIS Solar Power Tower Plant in France started operation in 1983. In 2004 the plant was modernized to 201 heliostats of 11,800 m^2 to produce 1 megawatt (MW) of electricity (**Figure 4.5**). In Seville, Spain the 11 MW PS10 solar power tower and 20 MW PS20 solar power tower have been recently completed. A 15 MW molten salt Solar Tres Power Tower is scheduled to be built in Andalusia, Spain consisting of 298,000 m^2 of solar collection surface on 2,590 heliostats. A 100 MW molten-salt-type central receiver solar power plant is planned with 4,000 to 5,000 heliostat mirrors for a site near Upington, South Africa.

The Odeillo-Font-Romeau Solar Furnace in Odeillo, France has 63 flat mirrors that automatically track the sun and concentrate light on a reflector (**Figure 4.6**). The reflector then focuses the sunlight to produce 1 megawatt of power and a temperature of up to 3,500°C in a solar oven. This oven is used to melt iron ore to produce steel.

Figure 4.5 THEMIS Solar Tower Power plant near Targassonne in the Pyrénées-Orientales of France.

Figure 4.6 Odeillo-Font-Romeau Solar Furnace in Odeillo, France.

Parabolic Trough Collector

Another type of solar furnace is a *parabolic trough collector*. It is constructed as a set of long parabolic mirrors shaped like half-pipes, with polished aluminum or silver coated surfaces. A Dewar tube runs along its length at the focal point to which the sunlight is reflected (**Figure 4.7**). The Dewar tube is constructed of two silvered wall layers with a vacuum between them. This design reduces heat transfer by radiation (prevented by the silvering) and conduction (prevented by the vacuum). This is similar to a Dewar flask that keeps cold liquids cold or hot liquids hot. Inside the Dewar tube a fluid, such as synthetic oil, is heated from the sunlight to over 400°C. The trough is usually aligned on a north-south axis, and rotated to track the sun as it moves across the sky each day. Maintenance on this system includes an automated washing mechanism that periodically cleans the mirrors.

The Solar Energy Generating Systems (SEGS) site is the largest solar energy generating facility in the world. It consists of nine separate parabolic trough collector systems located in California's Mojave Desert with a 354 MW installed capacity (**Figure 4.8**). The facility uses natural gas along with the parabolic trough collector to generate electricity with 90% of the electricity produced by sunlight. Natural gas is only used when the solar power is insufficient to meet the demand.

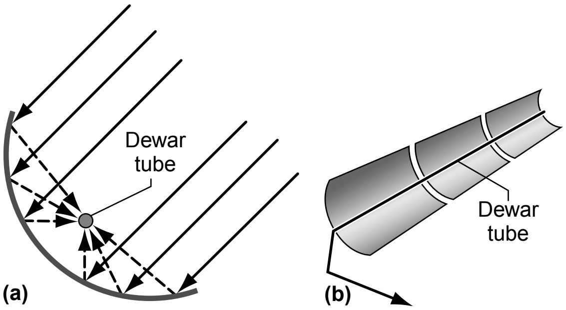


Figure 4.7 (**a**) Cross-section through a parabolic trough collector showing the reflection of energy to a Dewar tube at its focal point. (**b**) An array of parabolic trough collectors connected together with a continuous Dewar tube.

Figure 4.8 Parabolic mirror arrays of Solar Energy Generating Systems (SEGS) facility in the U.S. Mojave Desert.

Photovoltaic cells

Photovoltaic effects that cause sunlight to produce a voltage can occur in semiconductors. A *semiconductor* is a substance that can conduct electricity under some conditions but not others, making it a good medium for the control of electrical current. Most commercial solar cells are made of crystalline or amorphous silicon semiconductors. When sunlight strikes N-type silicon, part of the light spectrum imparts enough energy to excite outer electrons in the silicon atoms. N-type silicon is fabricated by adding an impurity, an element of a valence of five such as phosphorus, to four valence silicon. This increases the number of outer free charges. The sunlight excited electron has enough energy to break free from the silicon and join others to produce a current of electricity that moves along elevated energy orbitals for electrons in the N-type silicon. A "hole" is also created where the electron has left. A potential barrier for electrons in the cell is set up using a junction with P-type silicon. P-type silicon is produced by adding an impurity of a three valence element such as boron to the silicon. This impurity takes away, that is accepts, weakly bound outer electrons from the four valence silicon creating a "hole." Therefore, electrons are favored in the N-type silicon and "holes" are favored in the P-type silicon. As an electron jumps from one silicon atom to another the electrons are observed to move to the N-type silicon and the holes to move to the P-type silicon. This causes an electric current with a voltage of about 0.5 volt to be produced between the N-type and P-type silicon (**Figure 4.9**). The amount of electrical current, or amperes, produced depends on the area of exposure of the solar cell and the intensity of sunlight. Remember that amperes × volts = watts. Photovoltaic cells are connected in series to increase current and in parallel to increase voltage.

Current energy efficiencies for capture of the sun's energy are 12% to 15% for single crystal silicon cells and 4% to 6% for cheaper amorphous silicon cells. The cost of photovoltaic cells has dropped from about $1,000 per watt in the 1950s to under $5 per watt at the present time. They can produce electricity for as little as 25 to 30 cents per kilowatt-hour.

The direct current produced by the cells is converted to alternating current (AC) with a power inverter. The inverter switches the + and – terminals 60 times a second creating a 60 cycles per second square wave, which is conditioned to produce the required sine wave. With AC, transformers can be used to change voltages, which allows efficient electrical transmission at high voltages. Nearly all commercial electricity is AC.

While many rooftop systems are installed worldwide the largest PV power plants in the world are in Olmedilla de Alarcón, Spain (60 MW), Puertollano, Spain (50 MW), Moura, Portugal (46 MW), and Waldpolenz, Germany (40 MW) (**Figure 4.10**). Either a fixed photovoltaic panel or a tracking system where the panel follows the sun across the sky is used.

Photovoltaic cells can be manufactured into flexible thin films although these are less efficient, but cheaper to make. Many of these are installed on roofs of buildings as well as incorporated into material for building facades in what is termed building-integrated photovoltaics (BIPV). Additionally, semitransparent thin film solar cells that use infrared light to create electricity have been developed. These can be applied to window glass or skylights to tint them to decrease the amount of sunlight that enters a room and also produce electricity.

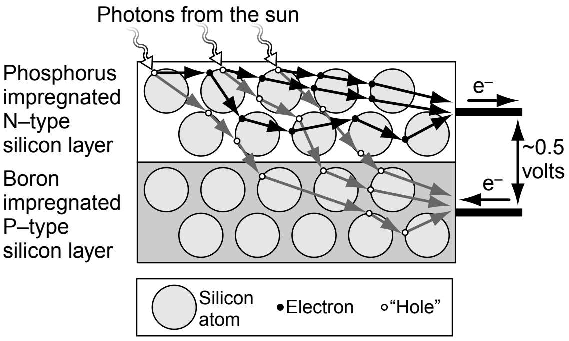


Figure 4.9 Schematic diagram of a photovoltaic cell. Black arrows show the movement of electrons and grey arrows the movement of holes.

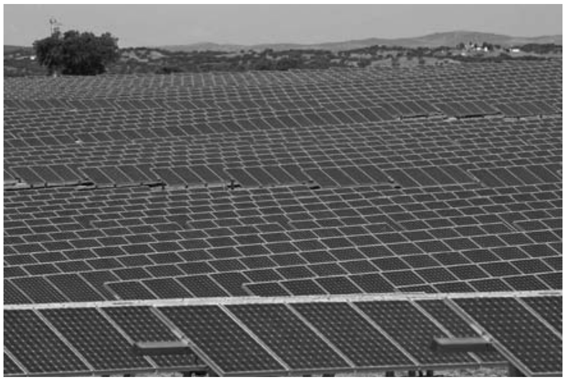


Figure 4.10 Photovoltaic power plant at Serpa, Portugal that includes a tracking system to follow the sun's path across the sky.

Fuel Cells for Energy and Hydrogen Gas

A *fuel cell* produces electricity in an electrochemical reaction similar to a battery. It, however, does not lose its charge with time because it runs on externally supplied fuel. In a hydrogen fuel cell with a proton exchange membrane (PEM) the fuel is hydrogen gas. In the reaction H_2 gives off electrons and is reduced to H^+ at an anode (negative electrode). The oxidant O_2 at a cathode (positive electrode) takes the electrons together with the H^+ and combines them to produce water (**Figure** 4.11). The maximum potential difference given in volts (V) is 1.23 V at 25°C but decreases to 1.18 V at 80°C. In real world situations at 80°C voltages near 0.7 V are obtained. The rest of the energy dissipates as heat.

Most electric motors to power vehicles operate at 200 to 300 V. This means a large number of fuel cells are connected in series to obtain the required voltage. The anode and cathode of a fuel cell are separated by a solid electrolyte. An *electrolyte* is a substance that has a high concentration of positive and negative charges mixed together, but is electrically neutral. A concentrated aqueous solution of NaCl is an electrolyte solution as NaCl is present as Na^+ and Cl^-. The electrolyte used in PEM cells is a solid membrane of dissociated poly-perfluorosulfonic acid containing H^+ and negatively charged membrane sites. The half-reaction at the anode of the PEM cell is:

$$H_2 \rightarrow 2H^+ + 2e^- \quad [4.1]$$

where e^- stands for an electron.

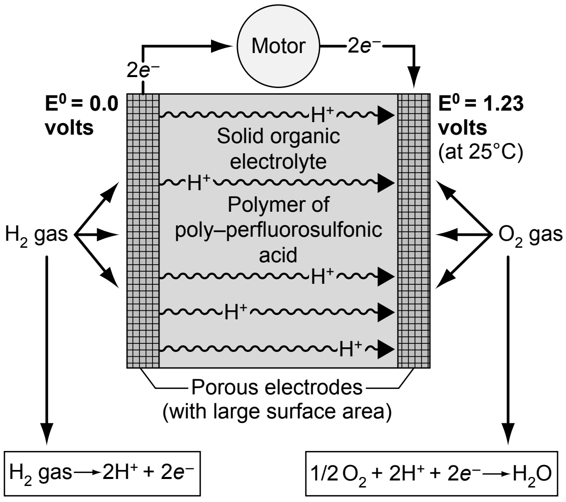


Figure 4.11 PEM fuel cell showing how H_2 and O_2 are reacted to produce electrons.

In order to increase the reaction rate so it can supply enough power to run a vehicle, a platinum (Pt) catalyst is used. With this catalyst much more rapid reactions than reaction [4.1] occur consisting of

$$H_2 + 2Pt \rightarrow 2Pt\text{–}H \quad [4.2]$$

and

$$2Pt\text{–}H \rightarrow 2Pt + 2H^+ + 2e^-. \quad [4.3]$$

Problems with using a Pt catalyst include its high cost and the fact that it is easily contaminated and, therefore, requires a relatively pure source of H_2 gas. At the cathode the reaction

$$4e^- + O_2 + 4H^+ \rightarrow 2H_2O \quad [4.4]$$

takes place. Note that the PEM cell produces only H_2O with no CO_2 emissions. If the reactions [4.2], [4.3], and [4.4] are summed the overall reaction is

$$2H_2 + O_2 \rightarrow 2H_2O. \quad [4.5]$$

Instead of using a fuel cell with its electrochemical reaction, the hydrogen gas can be burned in air that is also given by reaction [4.5]. The heat that is produced could be used to boil water and run a turbine to rotate a generator to produce electricity. The advantage of the fuel cell is that much more electricity can be produced for a given oxidation of H_2 as little waste heat is produced and a turbine and generator are not required.

Many kinds of fuel cell reactions that produce electricity are possible depending on the application. Given in **Table** 4.2 is a list of some common fuel cells and their characteristics. The PEM fuel cell is used in vehicles because it starts up quickly and has a low operating temperature. Vehicles run with a fuel cell would not have

Table 4.2 SOME COMMON FUEL CELL TYPES.

FUEL CELL NAME	ELECTROLYTE	OPERATING TEMP, C°	ELECTROCHEMICAL REACTIONS	APPLICATIONS	ADVANTAGES
PEM (Polymer Exchange Membrane)	Solid organic polymer of poly (perfluorosulfonic) acid	60–100	An: $H_2 \rightarrow 2H^+ + 2e^-$ Cat: $0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$ Cell: $H_2 + 0.5O_2 \rightarrow H_2O$	Electric utility Portable power Transportation	Solid electrolyte reduces corrosion Low temperature Quick start up
AFC (Alkaline)	Aqueous solution of KOH in a matrix	90–100	An: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ Cat: $0.5O_2 + H_2O + 2e^- \rightarrow 2OH^-$ Cell: $H_2 + 0.5O_2 \rightarrow H_2O$	Military space	Cathode reaction faster in alkaline electrolyte—so high performance
PAFC (Phosphoric acid)	Liquid phosphoric acid soaked in a matrix	175–200	An: $H_2 \rightarrow 2H^+ + 2e^-$ Cat: $0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O$ Cell: $H_2 + 0.5O_2 \rightarrow H_2O$	Electric utility Transportation	Up to 85% efficiency in cogeneration of electricity and heat Can use impure H_2 as fuel
MCFC (Molten carbonate)	Liquid solution of Li, Na, and/or K carbonate soaked in a matrix	600–1000	An: $H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$ Cat: $0.5O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$ Cell: $H_2 + 0.5O_2 + CO_2 \rightarrow H_2O + CO_2$	Electric utility	High temperature advantages of higher efficiency, inexpensive catalysts and more flexibility in fuel types
SOFC (Solid oxide)	Solid Zr oxide with a small amount of yttria, (Y_2O_3)	600–1000	An: $H_2 + O_2 \rightarrow H_2O + 2e^-$ Cat: $0.5O_2 + 2e^- \rightarrow O_2$ Cell: $H_2 + 0.5O_2 \rightarrow H_2O$	Electric utility	High temperature advantages (see MCFC) Solid electrolyte advantages

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an internal combustion engine but an electric motor instead. The difference between a fuel cell-powered electric vehicle (EV) and a battery-powered EV is that the fuel cell vehicle requires a supply of hydrogen gas and the battery-powered vehicle requires recharging batteries when their charge is low.

Water Power

Water wheels have been used at least back to 240 BC to grind grain and probably much earlier to help control water flow in crop irrigation. The first documented industrial use of hydropower to generate electricity occurred in 1880 when direct electric current was supplied to light a chair factory in Grand Rapids, Michigan. Water power uses the kinetic energy of the movement of water. This can be the movement of ocean water as well as water transported in rivers.

Ocean Power

Electrical power is produced with the aid of ocean tides. Tidal power then converts the potential energy of water with changing tides into the kinetic energy of moving water to make electricity. In terms of renewable energy sources, tides are much more predicable than wind or solar energy. Tidal barricades can be used to control differences in height between high and low tides. The barricades are dams built across the entire width of an arm of the ocean that extends inland such as in a bay at the mouth of a river. Shown in **Figure** 4.12 is the Rance Tidal Power Station located on the Rance River in France.

Another way to produce tidal power is to use the kinetic energy of moving water in a current in a *tidal estuary* as tides rise and fall to power a turbine under the water (**Figure** 4.13). This is similar to windmills using moving air. Because of the lower construction cost and lower ecological impact compared to a tidal barricade this method is gaining in popularity.

Wave power is another type of ocean power where energy from surface waves is employed to generate electricity or pump water. The energy of the rising and falling motion of waves can be captured by a buoy or other floating object. This kinetic energy is applied to drive a turbine to produce electricity. The world's first commercial wave farm is located 5 km off the Portugal coast at the Aguçadoura Wave Park. It can produce 2.25 MW of electricity and plans to increase its capacity to 21 MW.

It has also been shown that the difference in higher temperature surface and cooler deep-water can be used to obtain energy in what is termed Ocean Thermal Energy Conversion (OTEC). Warm seawater is placed in a low-pressure container where

Figure 4.12 The Rance Tidal Power Station produces electricity with 24 turbines and has a peak electrical power output of 240 MW.

Figure 4.13 Proposed design for electrical power generation from tidal currents.

it vaporizes until it cools to the lower temperature. The expanding vapor is used to drive a low-pressure turbine to produce electricity. In 1993 a power plant at Keahole Point, Hawaii, produced 50 kW of electricity during an OTEC experiment.

Hydroelectric Power

Modern hydroelectric power plants convert the potential energy of dammed water in reservoirs on rivers into electricity. The kinetic energy of the falling water drives a water turbine, which powers an electric generator. In 2010 there was 860 gigawatts (GW) of generating capacity worldwide in hydroelectric power plants producing 3,400 TWh of electricity. One TWh (terawatt hour) equals 10^{12} watt-hours. This makes hydroelectric power plants the largest source of renewable energy accounting for ~16% of the world's electricity usage. The world's 10 largest hydroelectric dams are listed in **Table 4.3**. With the completion of the Three Gorges Dam China produces the most of any country. China is also in the process of building a significant number of new large hydroelectric dams which will have a combined generating capacity of over 50 GW. Problems with constructing dams for power production are outlined when dams and water resources are discussed in a following chapter.

Table 4.3 Ten largest hydroelectric power plants.

NAME	COUNTRY	YEAR OF COMPLETION	RIVER DAMMED	TOTAL CAPACITY (GW)	ANNUAL ELECTRICITY (TW HRS)	AREA FLOODED (KM²)
Three Gorges Dam	China	2009	Yangtze	22.5	80.8	632
Itaipu	Brazil/ Paraguay	1984	Paraná	14	94.7	1,350
Guri (Simón Bolívar)	Venezuela	1986	Caroni	10.2	46	4,250
Tucuruí	Brazil	1984	Tocantins	8.37	21	3,014
Sayano Shushenskaya	Russia	1985/1989	Yenisei	6.4	26.8	621
Krasnoyarskaya	Russia	1972	Yenisei	6	20.4	2,000
Grand Coulee	U.S.	1942/1980	Columbia	6.809	22.6	324
Robert-Bourassa	Canada	1981	La Grande	5.616		2,835
Churchill Falls	Canada	1971	Churchill	5.429	35	6,988
Longtan Dam	China	2009	Hongshui	6.3	18.7	

Shown in **Figure** 4.14 are the amounts of hydroelectric power production in million metric tons of oil equivalent, Mtoe, for 2011 for the countries that produce the most hydroelectric power. One can compare these values to the total world energy usage in Figure **PT1.2** in the introduction of Part One for 2011 where about 13.5 thousand Mtoe were used.

Figure 4.15 displays a cross-section through a hydroelectric dam. The conversion of potential energy to electrical energy is 80% to 90% efficient, as opposed to 35% to 40% for burning fossil fuels. The greater efficiency occurs because no steam with its heat loss needs to be produced to run the turbine. Also hydroelectric generators can be powered up quite rapidly, making it an excellent backup system when additional electricity is needed in a power grid.

Because of the efficiency and rapid response, in some locations pumped-water storage facilities have been constructed. When there is low electrical demand, the additional generation capacity is used to power a water pump that pumps water into a higher elevation reservoir. When electrical demand is higher than average, water falling through a turbine from the high elevation reservoir drives an additional electrical generator. About 70% to 85% of the electricity used to pump the water to the higher reservoir is recovered when the falling water is used to power an electric generator. Such an energy storage facility is shown in **Figure 4.16**.

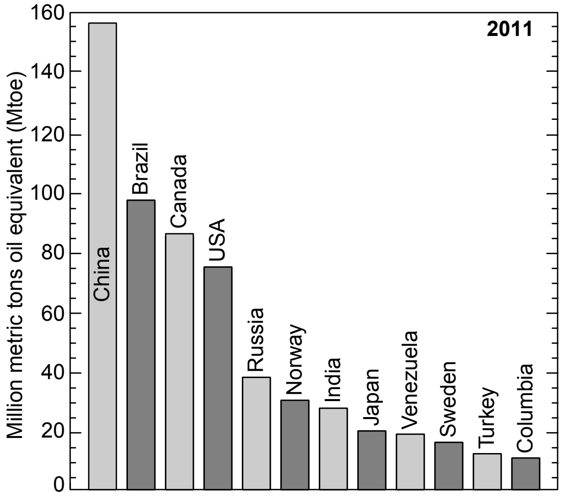


Figure 4.14 Hydroelectric power production in million metric tons of oil equivalent (Mtoe) displayed for the countries that produce the most hydroelectric power. (Data from: *BP Statistical Review of World Energy*, June 2010.)

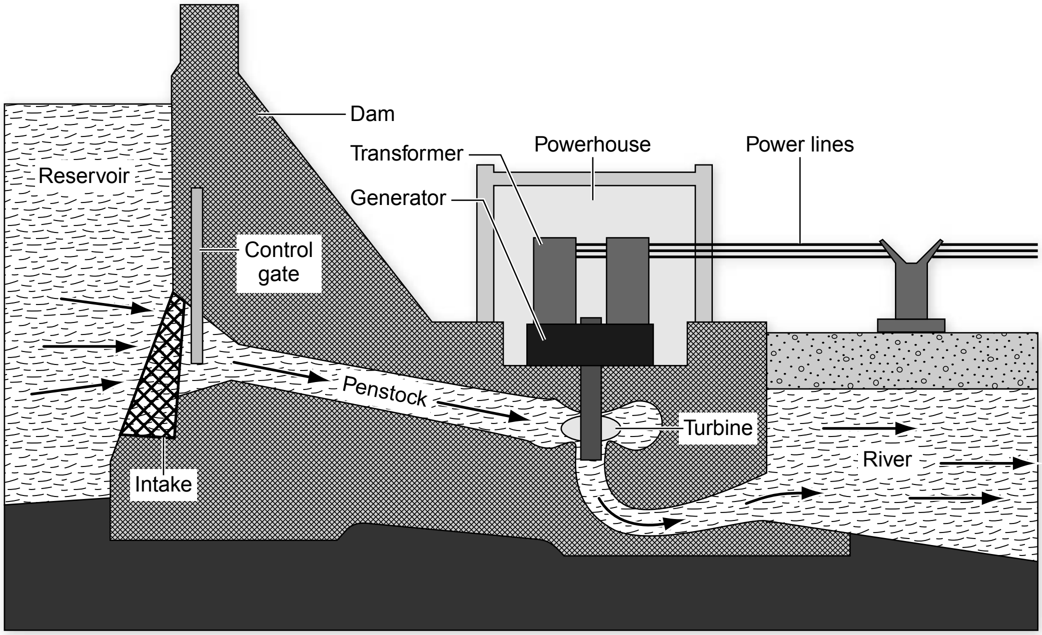


Figure 4.15 Cross-section through a hydroelectric dam.

Figure 4.16 Koepchenwerk pumped-storage facility with a net storage of 1.5 million m3 located along the Hengsteysee reservoir on the Ruhr River, near Dortmund, Germany.

Electrical Power Grid

An *electrical power grid* is a set of power plants and energy storage facilities, transmission circuits, substations, and connected electrical users (**Figure** 4.17). A problem with the power grid is the difficulty in storing significant quantities of electrical energy in the system. A system of controls is required to match supply and demand to avoid brownouts and blackouts. *Brownouts* occur when the power supplied drops below the demand. *Blackouts* occur when there is no power at all transferred to the end user.

A voltage step-up transformer, which lowers the current, is used before the electric power from a power plant is put into the transmission lines to increase transmission efficiency. The high voltage transmission lines are uninsulated aluminum. Aluminum is used rather than copper because of its lower weight and cost. Transmitting electricity thousands of kilometers is reasonably cheap and efficient. Costs are on the order of US$ 0.005 to 0.02 per kilowatt hour (kWh). It is estimated that in the United States about 6.5% of the energy is lost during transmission and distribution judging from the difference in energy produced by power plants and that metered by end customers.

An average U.S. household uses about 10,650 kWh of electricity each year. In mid 2009, the average cost was 12¢/kWh, varying from a 7¢/kWh low average in North Dakota to 26¢/kWh high average in Hawaii. Therefore, transmitting costs are a small part of total costs. A problem with connecting a far away power source is the construction of transmission lines is expensive.

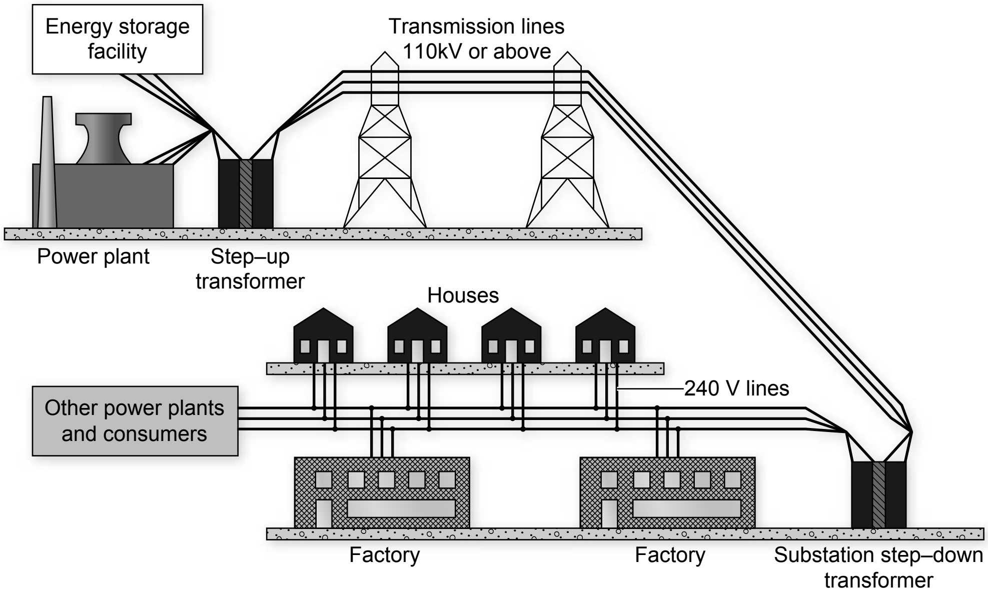


Figure 4.17 Electrical power grid with an energy storage facility.

Wind Power

The conversion of the kinetic energy of the wind into a useful form of energy is termed wind power. Historically this energy has been harnessed by sails on ships, windmills to move blades or grinding stones to "mill" grain, and windmills on ranches and farms to pump water from underground wells. Recently the use of wind turbines to produce electricity has been growing rapidly. At the end of 2011, worldwide capacity of wind-powered electrical generators was 238 GW, about 1.6% of worldwide electricity usage (**Figure 4.18**). The electrical wind power production by country for 2011 is given in **Table 4.4**.

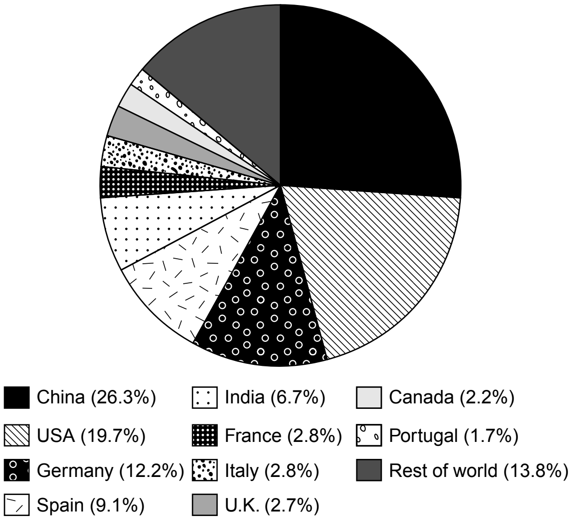


Figure 4.18 Countries with the largest installed wind turbine capacity of the 238.35 gigawatt total capacity as of 2011. (Data from: Global Wind Energy Commission, *GWEC Global Wind Statistics 2011*.)

Wind is produced by differential heating of the earth. The earth's poles receive less energy from the sun than the equator. Also, the continents heat up and cool down more rapidly than the ocean does. The differential heating drives a global atmospheric convection system. Most of the energy in these wind movements can be found at high altitudes where continuous wind speeds of over 160 km/h occur.

Wind-produced electricity is generated from turbines that often are as tall as a 20-story building and have two or three long blades. The wind spins the blades, which turns a shaft connected to a generator that produces electricity. Most common are wind turbines that rotate blades about a horizontal

Table 4.4 2011 WIND POWER ELECTRICAL CAPACITY AND WORLD PERCENT OF CAPACITY.

NATION	GW CAPACITY	PERCENT OF WORLD TOTAL
China	62.73	26.3
USA	46.92	19.7
Germany	29.06	12.2
Spain	21.67	9.1
India	16.08	6.7
France	6.80	2.8
Italy	6.75	2.8
U.K.	6.54	2.7
Canada	5.27	2.2
Portugal	4.08	1.7
Total	**238.35**	**100%**

Data from: BP Statistical Review of World Energy, June 2009.

axis but vertical axis wind turbines are also used and look like giant eggbeaters (**Figure** 4.19).

Shown in **Figure** 4.20 is the internal working of a wind turbine. The wind rotates blades, which turn a low-speed shaft that is geared to rotate a high-speed shaft inside a generator. A device, termed an anemometer, measures wind speed and a wind vane determines its direction. This information is sent to a controller and drive to adjust the direction and maximize the efficiency of the turbine.

In order to evaluate the wind resources in a particular area it is important to know that the energy available is proportional to the cube of wind speed. Therefore, twice the wind speed increases the available energy by a factor of eight. The wind is seldom present in a steady, consistent flow. It can change with the time of day, season, height above ground, and type of terrain. Typically annual average wind speeds of 5 m/s (11 miles per hour) or greater are required for electrical grid connection.

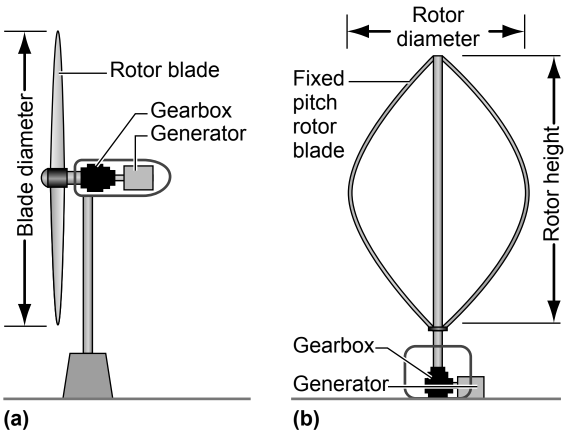


Figure 4.19 (**a**) Horizontal axis and (**b**) vertical axis (egg beater) wind turbine.

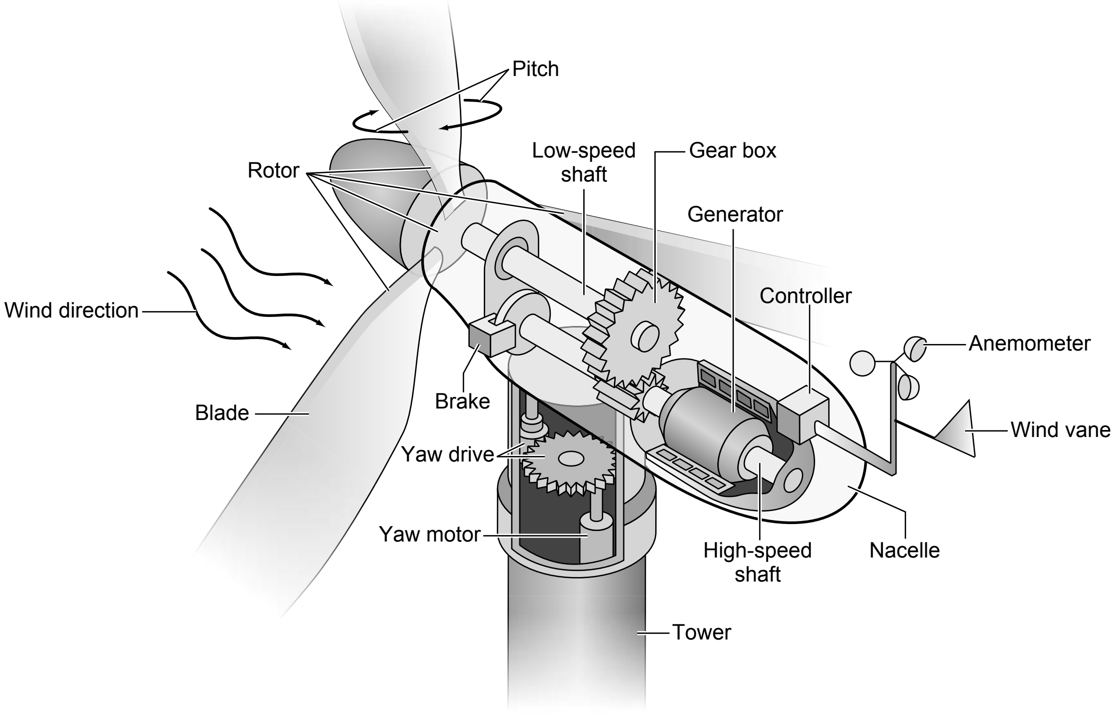


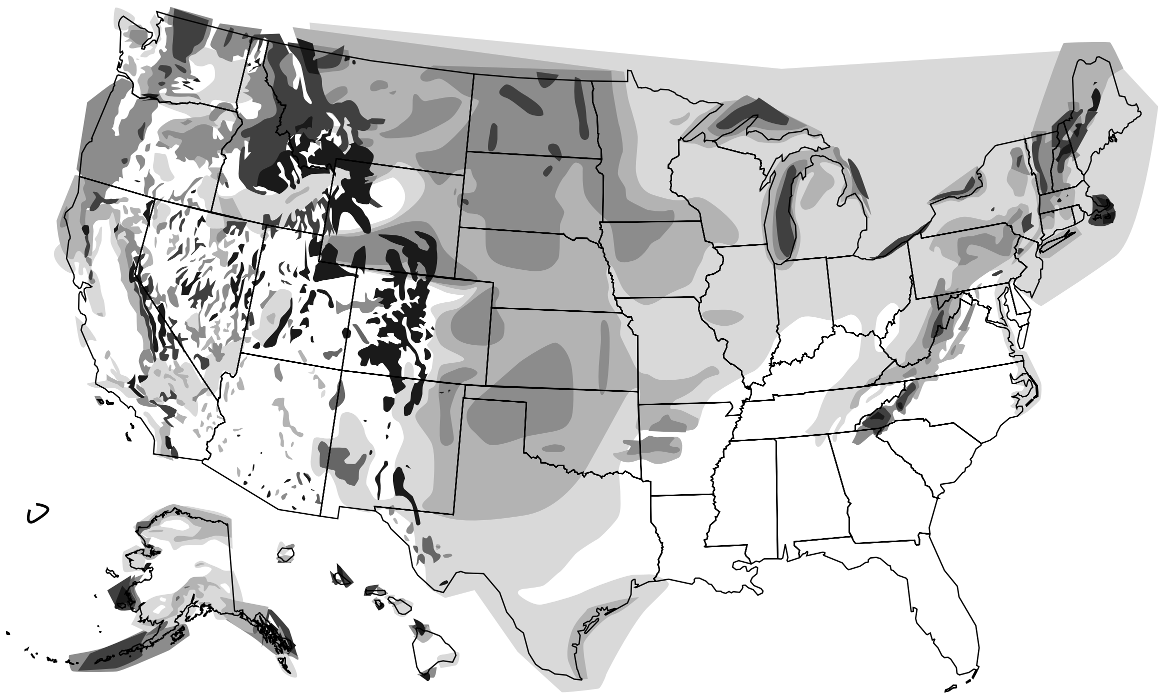
Figure 4.20 Wind turbine with parts labeled. (Reproduced from Wind Program, U.S. Department of Energy.)

Power density is a useful measure of wind energy. This is energy per time per unit area of wind capture. Because air has mass it has kinetic energy equal to $\frac{1}{2} m v^2$ where m is mass and v is its velocity. Remembering that mass = density × volume, to determine wind power, P, the relationship is

$$P = \tfrac{1}{2} \rho A v^3 \qquad [4.6]$$

where ρ stands for air density (~1.225 kg m^{-3} at sea level and less at higher elevations) and A denotes the area of wind captured perpendicular to its velocity. Wind speed and therefore wind power increases with height. At a particular location these are typically considered at standard heights of 10 and 50 m. As given by the wind power classes in **Figure 4.21**, sites with a rating of 4 or higher are preferred for large-scale wind electrical generation plants.

The wind blows faster at higher altitudes because there is less drag from the earth's surface. Tower heights approximately two to three times the blade length have been found to balance material costs of the tower against better utilization of the expensive magnets in the electrical generators. Typical modern wind turbines have diameters of 40 to 90 meters and are rated between 500 kW and 2 MW although a few are rated as



	10 m height		50 m height	
Wind power class	Wind power Density (w/m^2)	Speed m/s (mph)	Wind power Density (w/m^2)	Speed m/s (mph)
1	0–100	0–4.4 (9.8)	0–200	0–5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1,000	9.4 (21.1)	2,000	11.9 (26.6)

Figure 4.21 United States annual wind power density. (Reproduced from Wind Energy Atlas of the United States/NREL.)

high as 6 MW. Turbine installations in hilly or mountainous regions tend to be on ridgelines. This is done to exploit the topographic acceleration as the wind accelerates over a ridge.

Because of the strong winds produced by the differential heating of the land and ocean surface each day, many turbine installations are on land within 3 kilometers of a shoreline or on the water within 10 kilometers of shore. Offshore wind turbines are less obtrusive than turbines on land, as their apparent size and noise is mitigated by distance. Also water has less surface roughness than land and the average wind speed is, therefore, usually higher over open water.

Concerns in Developing Wind Power

There are some environmental concerns with the use of wind turbines. These include bird fatalities by flying into the rotating blades. Statistical analysis appears to indicate bird fatalities are minimal when compared to other electrical power sources. There is, however, a significant problem with bat fatalities. Bats that use trees as roosts appear to be attracted to the wind turbines. This is a particular problem in migration and mating seasons.

Noise pollution is another concern. Wind turbine blades produce a low-frequency buzzing, swishing sound when contacting the air. The turbine's internal gears also make mechanical noise. Both types of noise have caused irritation to some individuals that are close to a wind turbine. Such concerns need to be addressed when siting wind turbines.

Concerns have also been expressed about the availability of rare earth elements going forward if wind power expands dramatically. The latest wind electrical generating technology uses special magnets made from neodymium and other rare earth elements that dramatically increase energy conversion efficiency. There is some worry about supply as the People's Republic of China dominates rare earth mining (see the chapter on specialty metals). They have been known to attempt to manipulate the market.

Biofuels

Biofuels are a wide range of alternative energy sources derived from recently living organisms. This includes biomass used for heating and to produce electricity as well as biodiesel and ethanol. Biomass heating and electrical production uses forest wood, agricultural residues, and urban as well as industrial waste as the energy source.

Forest wood is burned in fireplaces, ovens, and furnaces. Worldwide it makes up almost 10% of the total primary energy supply. More than 2 billion people use wood energy for cooking and/or heating, particularly in developing countries. For many it is the only affordable and locally available source of energy.

In developed countries urban waste trash is burned to produce both heat for industrial operations and steam for electricity generation. There were 87 trash-burning power plants in the United States as of 2011. Other developed countries have many more per capita. There are about 200 across Europe.

Another biofuel is methane released from organic mater decay in waste dumps and landfills by the reaction:

$$\underset{\text{Organic matter}}{2CH_2O} \rightarrow \underset{\text{methane}}{CH_4} + CO_2. \qquad [4.7]$$

Most landfill gas occurs in developed countries, where the levels of waste production tend to be highest. This gas is being collected in many locales and the methane is separated from the CO_2 and used as an energy source.

Using biomass diverts wood waste from landfills and conserves fossil fuels but increases carbon addition to the atmosphere as biomass has lower energy content per carbon combusted than fossil fuels and is no longer serving as a sink for atmospheric carbon. Crops grown for their energy content include hybrid poplar, willow trees, and switchgrass. If biomass is produced for its energy it takes agricultural land out of food production.

Biodiesel is a renewable transportation energy source that can be used in standard diesel car and truck engines. Nearly 85% of the world's biodiesel is supplied by European Union countries. Biodiesel is generated from vegetable oil, mainly olive, rapeseed and soybean oils, and animal fat. Soybean oil accounts for almost 90% of production in the U.S., but waste vegetable oils after food frying, waste animal lard and grease, and chicken fat are also processed into biodiesel.

With higher energy costs a number of companies have looked into algae production as a biofuel energy source. The attractiveness is that waste water or ocean water rather than freshwater can be used to grow the algae, unlike most other biofuel sources. Also microalgae grow faster than terrestrial crops grown for their energy. Carbohydrate in the algae can be fermented into ethanol and oil present in the algae can be processed to produce biodiesel.

Ethanol

Ethanol (C_2H_5OH) is a short, straight carbon chain liquid also called ethyl alcohol. It is the intoxicating ingredient present in alcoholic beverages. The largest single use of ethanol is as an additive making up about 10% of petroleum motor fuel in over 20 countries. This fuel can be burned in vehicles designed to run on 100% petroleum. This use of ethanol is generally motivated by a desire to conserve petroleum.

Vehicle engines with specially designed engines that burn nearly pure ethanol fuel are found in Brazil as well as the United States. In Brazil the fuel used is 96% ethanol and 4% water. The 4% water is a product of the distillation process. In the U.S. E85 is used, a fuel containing 85% ethanol and 15% gasoline. The 15% gasoline is added to increase the vapor pressure of ethanol. Pure ethanol has problems igniting in cold weather because the vapor pressure in the combustion chamber is so low. Ethanol when burned releases about 21.2 megajoules (MJ) per liter of energy while regular gasoline releases 44.4 MJ per liter. However, because higher, more efficient compression can be used in an E85 engine the decrease in mileage is only about 25% over regular gasoline.

Ethanol can be produced by the hydration of ethylene, C_2H_4, during petroleum refining by the reaction:

$$C_2H_4 + H_2O \rightarrow C_2H_5OH. \qquad [4.8]$$

However, most ethanol is produced commercially by grinding grain kernels into flour. The starch in the flour is converted to sugar with the help of enzymes. The sugars are then fermented with the aid of yeast to create carbon dioxide and ethanol by the reaction:

$$\underset{\text{glucose}}{C_6H_{12}O_6} \rightarrow 2C_2H_5OH + 2CO_2. \qquad [4.9]$$

The 12% to 15% ethanol produced can be separated from the mixture by fractional distillation due to their differences in boiling temperatures. A mixture of 96% ethanol and 4% water is produced at 78.2°C. Dehydration of this ethanol by a molecular sieve that absorbs water but allows ethanol to pass is typically used to remove the water in the U.S.

The economics of reactions [4.8] and [4.9] depends on the relative prices of petroleum and grain. For the recent past, fermenting grain sugar has been the dominant production method with less than 5% produced from petroleum.

Ethanol production in 2009 was equal to 38 million metric tons of oil equivalent (Mtoe) (**Table 4.5**) or 20 billion gallons. The United States produced a little over half of this from corn kernels with Brazil producing another 1/3 of the world total mainly from sugar cane. A problem with pure ethanol distribution is that it easily absorbs water. Therefore, it cannot be efficiently shipped over long distances through underground pipelines as is done with liquid hydrocarbons.

Rather than using starches and sugars ethanol can also be produced from the cellulosic nonedible parts of plants composed of cellulose and hemicellulose. They, together with lignin, are the dominant components of woods and grasses. Ethanol from cellulosic plant material holds great promise due to the widespread availability and relatively low cost. However, cellulosic plant material requires a greater amount of processing

Table 4.5 Countries with largest 2011 ethanol production of the world's total of about 22.4 billion U.S. gallons.

COUNTRY/ REGION	FUEL ETHANOL
United States	13,900
Brazil	5,573
European Union	1,199
China	555
Canada	462

In millions of U.S. gallons.

than is needed with starches and sugars. Enzymes are first used to break down the complex cellulose structure into simple sugars before fermentation is undertaken. Although a number of fermentation processes are technically feasible, to date cost-effective processes have been difficult to achieve because of the complexity of pretreatment and fermentation to alcohol required.

Geothermal Energy

The temperature of the earth increases downward. Therefore heat energy can be transferred from depth in the earth to the surface where it can be used as an energy source, termed geothermal energy. Geothermal energy is nearly a totally renewable energy resource as the extraction of heat in water is replaced by more heat from the rocks below and natural radioactive decay. It is not totally renewable as in some cases the extraction of heat occurs more rapidly than it can be replaced. However, geothermal energy can provide continuous base-load power with low environmental impact. *Base-load power* means producing power at a dependable rate 24 hours a day and 365 days a year except for routine maintenance. The main problem with tapping energy from the interior of the earth is the high capital costs because of the need to drill wells. Geothermal areas can produce electricity quite inexpensively once the plant is constructed because no external energy is required to produce steam to power a turbine.

About 10.7 GW of geothermal electric capacity was installed around the world as of the end of 2009, generating 0.3% of global electricity demand. The U.S. has 28.8% of the world's total installed geothermal power capacity followed by 17.8% for the Philippines and 11.2% for Indonesia. There is an additional 28 GW of direct heat geothermal resources installed worldwide for district heating, space heating, spas, industrial processes, desalination, and agricultural applications.

The heat that is available in the earth is different depending on the location. In areas that have experienced recent volcanic activity there are generally hot rocks at shallow depths. Circulating groundwaters are heated to high temperatures by these rocks and brought naturally to the surface in some areas. Surface expressions are hot springs, mud pots, geysers, and steam vents. These can be excellent places to construct a geothermal power plant because the hot water can be used to produce electricity. Given in **Figure 4.22** are the potential geothermal resources of the United States. Note the western U.S. has the high heat fluxes needed as a result of tectonic activity in the Sierra Nevada Mountains, Great Basin, and Rocky Mountains, which brought hot rocks and magmas closer to the surface.

Geothermal Power Plants

There are three geothermal power plant technologies being used to convert hot water in the earth to electricity. The conversion technologies are *dry steam*, *flash steam*, and *binary cycle boiling* depending on the temperature of the hot water.

Dry steam power plants are the most common form of geothermal power plant. They use water at depths with temperatures greater than 182°C. The hot water is pumped to the surface from the geothermal production zone under a high enough pressure that it remains liquid. Therefore, the pressure needs to be greater than the water's boiling pressure. When it reaches the surface the pressure

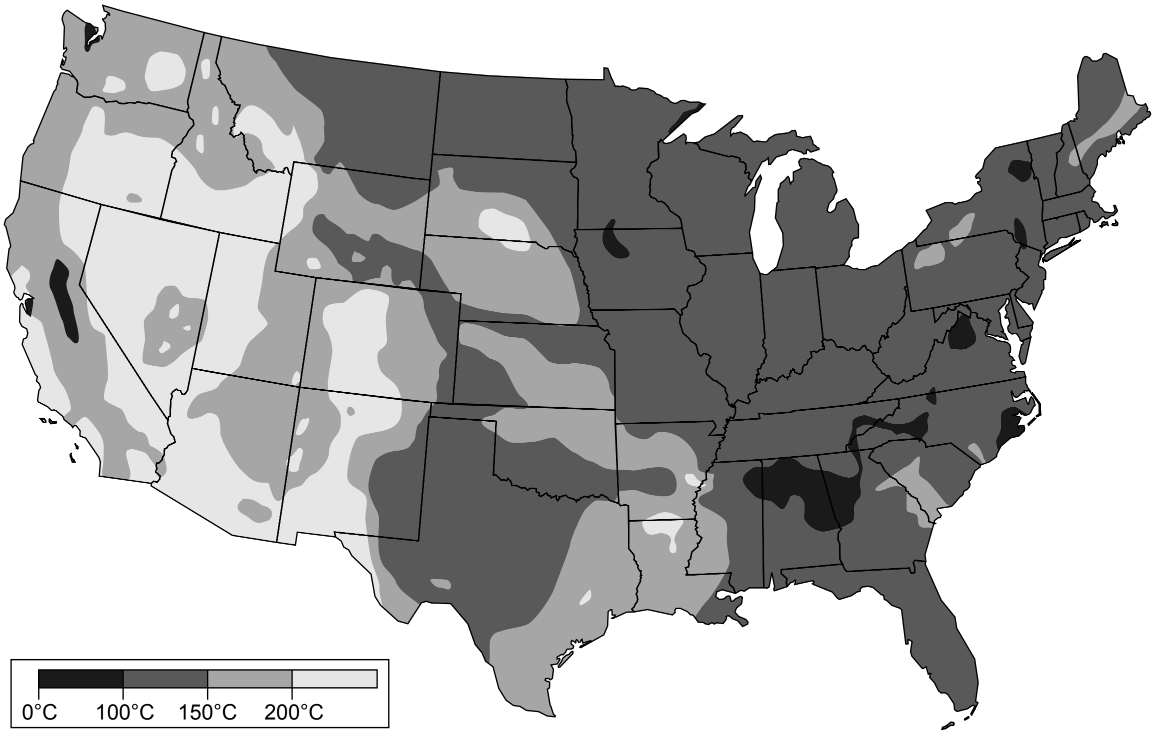


Figure 4.22 Geothermal resources of the United States indicating estimated subterranean temperatures at a depth of 6 kilometers. (Adapted from NREL, U.S. Department of Energy.)

is reduced to near 1 atmosphere (atm). As a result of the high temperature all the water is converted to steam, termed dry-steam. After the steam is run through a turbine to generate electricity it is cooled so it is transformed back to liquid water and returned to the reservoir to be heated again by the hot rocks in the production zone as shown in **Figure 4.23**. This is what is done in the Geysers area of California, the world's largest dry-steam geothermal production field where 1500 MW of capacity has been installed.

If the water is at lower temperatures and therefore contains less heat, a flash-steam geothermal plant can be constructed. Flashing is the process of rapidly dropping the pressure on water to suddenly produce steam by opening the hot water to a low pressure space. In this type of geothermal power plant the flashing of the water from the production zone produces some steam but a brine solution is also produced. It is brine because the hot water typically has many dissolved constituents, which become concentrated with the loss of steam. The steam is separated from the waste brine and run through a turbine. This steam is cooled and injected together with the brine back into the production zone as shown in **Figure 4.24**. Liquid-dominated systems, such as at Wairakei, New Zealand, produce a mixture of steam and hot water on flashing.

In areas where groundwater is heated to below 175°C it can't be flashed to produce significant steam, but the heat can be extracted by using a heat exchanger in a binary flash system. Heat is transferred from the geothermal fluid to a working fluid. The working fluid is often butane or pentane, which have the low boiling temperatures at 1 atm required of −0.5°C and 36°C, respectively. When this working fluid is vaporized by boiling, the vapor can be directed to a turbine to power an electric generator. After it is run through the

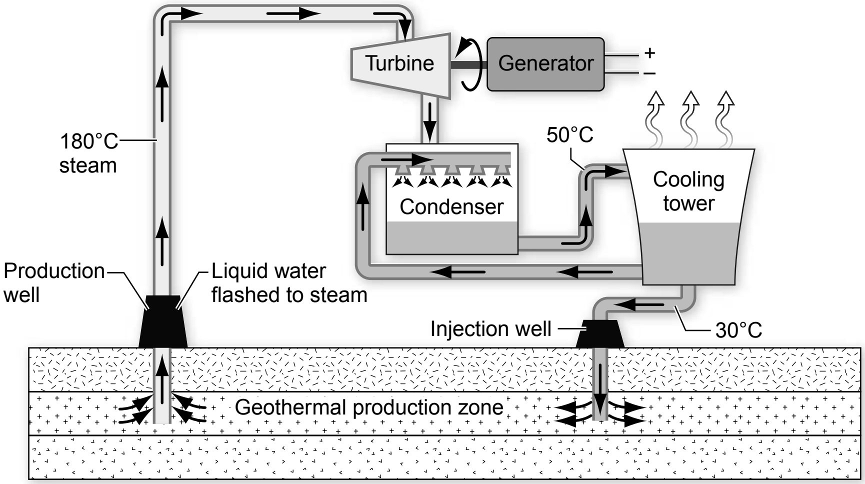


Figure 4.23 Dry-steam geothermal power plant.

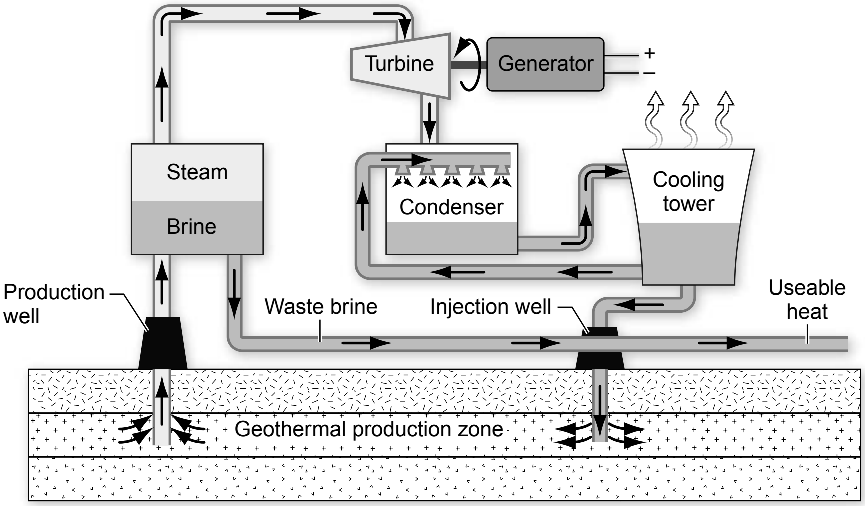


Figure 4.24 Flash-steam geothermal power plant.

turbine the vapor is condensed to a liquid by cold air or water and fed back into the heat exchanger as shown in **Figure 4.25**. Binary cycle geothermal plants are in operation at Mammoth Lakes, California, Hilo, Hawaii, and Steamboat Springs, Nevada.

There is an enormous untapped geothermal energy resource base associated with oil and natural gas operations. In many of these wells hot water of less than 150°C is extracted along with the oil and natural gas. While not being utilized presently, this hot water can produce electricity by running it through a binary flash system (McKenna et al., 2005). The resource potential is estimated to be 985 to 5,300 MW using the water-rich fluids currently being produced during production of oil and natural gas in seven U.S. Gulf Coast states.

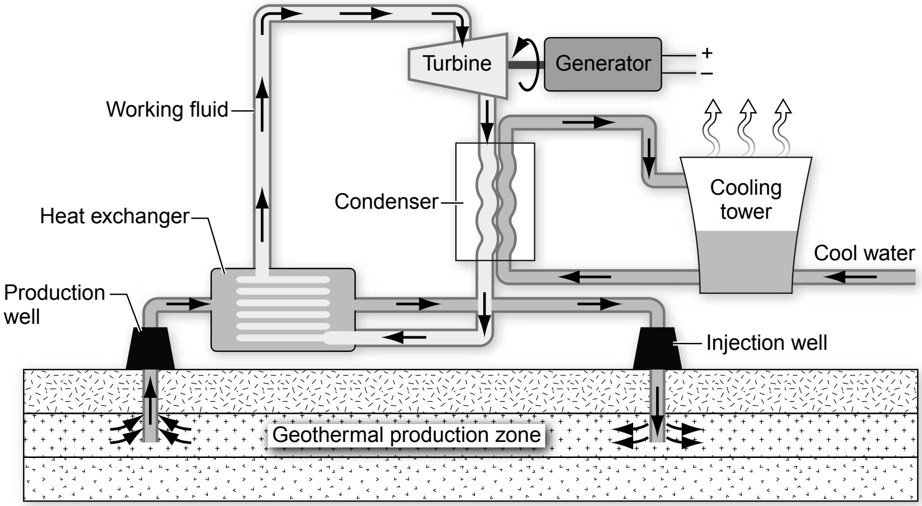


Figure 4.25 Binary cycle geothermal power plant.

Concerns in Developing Geothermal Power

The biggest issues with geothermal power revolve around water usage. The hot water withdrawn from underground can contain toxic elements such as mercury. Care must be taken so that after its use it can be safely injected underground and does not contaminate any drinking water supplies. Also, significant quantities of freshwater are used to cool used steam as is true of other power plants that use steam. In areas where freshwater is not plentiful, developing geothermal power decreases the amount of water available for farming and residential use.

At some geothermal production plants land subsidence has occurred due to loss of the extracted fluid. The change in the fluid regime underground has also been known to cause small earthquakes. Of most concern is with the development of enhanced geothermal systems.

Enhanced Geothermal Systems

Hot rocks at depth are often nonporous and do not allow the circulation of water. A geothermal resource can be developed in these rocks by fracturing them to allow fluid flow. Recently crystalized granites with elevated geothermal gradients have been targeted. Cold water is pumped down into the granite at high pressure through a borehole typically drilled to a depth of 3 to 4 km. As the water warms it expands and stresses the granite. The granite then factures, increasing the rock's permeability. A second borehole is drilled nearby to recover the heated water from the fractured rock, and this water is used to make electricity.

In Cooper Basin, South Australia, Geodynamics Limited is in the process of developing a 25 MW enhanced geothermal power system (EGS) by December 2013 and is targeting production of more than 500 MW by 2018 by fracturing hot granites at depth.

Geopressured Geothermal Energy

The U.S. Gulf Coast region is underlain by many deeply buried, low salinity sandstone reservoirs containing water in excess of hydrostatic pressure, that is, *geopressured*, and it often approaches the lithostatic pressure produced by the weight of the rocks themselves. Because the geothermal gradient is high in the region the fluid in these reservoirs is at significantly elevated temperatures. It has also been demonstrated that at least some of this water contains small amounts of dissolved methane gas. This geothermal resource is located near the petroleum refining plants along the Texas and Louisiana Gulf Coast, one of the major energy consuming areas in the United States. Dorfman and Kehle (1974) estimate the energy contained within the geopressured aquifers of Texas may be as great as 20,000 MW centuries excluding the natural gas production that could occur.

Direct Use Geothermal

Warm water that is not hot enough to produce electricity can be tapped for space heating of homes and greenhouses. In Iceland, which sits on recently formed basaltic rocks of the mid-Atlantic ridge, groundwater of temperatures between 60° to 80°C is used to heat homes. Besides heating homes, warm water in shallow reservoirs throughout the world is used to heat schools, offices, health spas, greenhouses, and fish farms.

Geothermal Heat Pumps

The heating and cooling needed for buildings can be done by extracting heat from and injecting heat into the earth with a *geothermal heat pump*. Geothermal heat pumps do not need high temperature water near the earth's surface and can therefore be used in areas with normal geothermal gradients. By pumping fluid through loops of pipe buried underground next to a building, these systems take advantage of the relatively constant temperature, 7° to 13°C of the earth's surface below that is heated by the sun. Heat can be transferred into buildings in winter and out of buildings in summer. There are about 300,000 heat pump installations in the United States. Switzerland and several other countries are implementing large heat pump programs. The geothermal heat pump shown in **Figure 4.26** only uses a small amount of energy to move water from one location to another with a fluid pump while controlling the temperature inside the building.

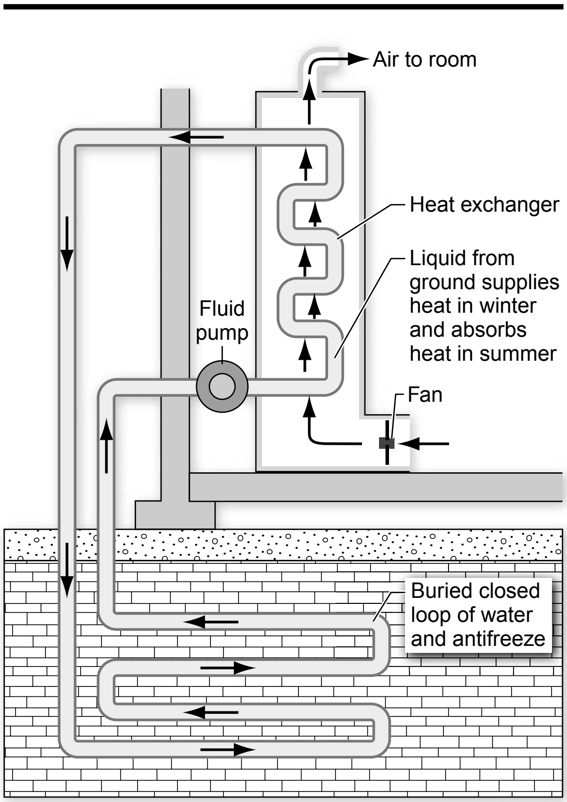


Figure 4.26 Geothermal heat pump.

A related system is used at Cornell University and Ithaca High School, New York. Here, a lake source cooling system transfers 4°C water from the bottom of nearby Cayuga Lake to a heat exchanger to cool water in the campuses-chilled water cooling systems. It then returns the water to the lake's surface. This replaces using 51 MW of electricity and conventional refrigerants to cool buildings. A similar system operates in Toronto, Canada using Lake Ontario water.

Total Cost of Electrical Production in the U.S. by Power Source

Total cost for the generation of electricity includes both power plant construction costs as well as electricity production costs. Each type of power plant is unique in the distribution of these costs. There are also regional differences in construction for the same power source including the external costs of required pollution abatement as well as load-balancing concerns that are not considered in **Figure** 4.27 where power source costs are compared. This means the lower value of the intermittent production from wind and solar is not factored into these costs. Decommissioning costs are included only for nuclear power. Nuclear power, however, does not include the cost to dispose of spent fuel. This is presently a U.S. government cost. Hydroelectric power total cost does not consider building the required dam, just the electrical generating facility. Also, costs in the figure are for 2009 and some adjustment likely needs to be made for any changes in the price of coal, natural gas, and uranium with time.

For hydroelectric power 2/3 of total costs is for construction and 1/3 production costs, whereas for solar it is almost entirely construction costs. A natural gas power plant is the least expensive type of power plant to construct per kwh produced with most costs from the purchase of natural gas. Nuclear power plants are expensive to construct but produce more useable energy than an average sized coal or natural gas power plant for the same cost of fuel.

What Figure 4.27 shows is that relative to the fossil fuels, coal and natural gas, electrical power from geothermal, hydroelectric, and nuclear are competitive. However, going forward both geothermal and hydroelectric are limited in their ability to expand in the future in industrialized nations as most prime locations have been exploited. As will be outlined in the next chapter nuclear power has significant safety concerns. The path to increased electricity production into the future is still not clear, but many options with their pluses and minuses exist. The preferred generating technology at a particular location will depend on the specific circumstances of the situation.

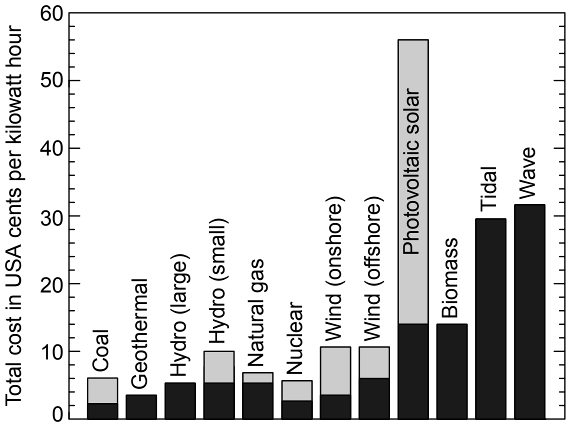


Figure 4.27 Electrical power production costs in U.S. cents per Kwh in 2009 for the indicated energy source. Lighter grey area indicates range of costs. (Data from: *U.S. Energy Information Administration's Annual Energy Outlook 2009*; biomass, tidal, and wind data from the U.K. Department of Trade & Industry, May 2007, *Energy white paper: Meeting the energy challenge,* recalculated to 2009 values.)

SUMMARY

Solar energy comes from a whole spectrum of different wavelengths. Some we can see (visible light), some are too short to see (ultraviolet light), and some are too long to see but we feel as heat (infrared). Humankind uses low-quality solar energy for heating and illumination. This energy is transferred by radiation, convection, and conduction. Solar furnaces focus sunlight and photovoltaic cells absorb sunlight to produce electricity.

Fuel cells produce electricity in an electrochemical reaction. A proton exchange membrane (PEM) fuel cell runs on hydrogen and produces only water as a reaction product. PEM cells are used to power motors in electric vehicles.

Electrical power can be produced by tides, ocean waves, and differences in surface and deep-water temperatures. Hydroelectric dams convert the potential energy of water into electrical energy and are quite efficient in the process. Electrical power grids produce and distribute electricity. The supply must be matched to demand.

Wind power converts the kinetic energy of air particles into useful energy. The turbines that are used are constructed and located to take advantage of maximum sustained winds. Because the temperature in the earth increases downward, the heat energy at depth can be brought to the surface by water in what is called geothermal energy. Different types of geothermal power plants are constructed depending on the temperature of the water, dry-steam, flash-steam, and binary-cycle boiling. Heat pumps can move heat from a higher temperature heat source to a lower temperature heat sink.

When total costs are considered a geothermal power plant is the least expensive way to produce electricity if water is hot enough to produce dry steam. Photovoltaic solar, tidal, and wave energy are the most expense ways.

KEY TERMS

base-load power
binary cycle boiling
blackout
brownout
conduction
dry steam
electrical power grid
electrolyte
energy convection
flash steam
fuel cell
generator
geopressured
geothermal heat pump
greenhouse effect
heliostat
infrared radiation
parabolic trough collector
photovoltaic cell
radiation
semiconductor
solar power
tidal estuary
turbine
ultraviolet radiation

PROBLEMS

1. a. How much electrical energy can be generated by all the water in a lake 2,000 meters wide by 8,000 meters long by 50 meters deep if all the water falls through a vertical distance of 650 meters? Assume that the electrical generator is 80% efficient and the density of water is 1.0 g cm^{-3}. Give your answer in joules.
   b. What would be the average electric power output in watts if this lake were drained over a period of one year?
2. If the wind speed increases by 60%, an ideal windmill will produce how much more power?
3. To heat an average house for one year in Provo, Utah takes about 10^7 kcal. Say you could get this heat by cooling off the rock under your yard by 10°C. If your yard is 30 m by 20 m, how deep a layer of rock (h) must you cool to extract this much heat? The heat capacity of rock is 0.21 kcal/kg/°C and the density of rock is ~2,700 kg/m^3.

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