Chapter 17

SOLAR ENERGY

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. The National Energy Strategy's renewable energy initiatives are based on these conclusions and on a clear understanding of the contributions that renewable energy can and cannot be expected to make. For example, given policies to address existing regulatory barriers and market imperfections, solar thermal or photovoltaic electricity technologies can compete today to provide electricity generation in remote locations and for peaking purposes.

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

The Administration supports fundamental and applied research that helps the renewable industry develop technologically advanced products. [...] Applied research into thin reflective membrane deposition, airfoil design, and solar module fabrication has reduced costs and increased productivity from solar thermal power plants, wind turbines, and flat plate photovoltaic arrays.
[…]

Programs supporting renewable electric supply will contribute 0.6 quads of primary energy in the year 2000, saving $4 billion in annual fuel costs and reducing 7 million metric tons of carbon-equivalent emissions.

(*Sustainable Energy Strategy*, 1995)

In Chapter 16 we discussed the following nondepletable energy sources: geothermal, wind, tidal, wave, hydroelectric and biomass energy. We saw that they *will not* solve the world's energy problems. But they are, they can be and they will be important on a local scale. In Chapter 14 we discussed nuclear fusion; it *could* solve all our energy problems, but many technical problems need to be overcome before it can be harnessed and commercialized. The production of electricity using fusion must go through the 'bottleneck' of thermal-to-mechanical energy conversion, which is inherently inefficient. The last energy source that we need to discuss, direct solar energy, *will* solve all society's energy problems, but not yet. Its efficient large-scale utilization is expected to become a reality some time in the 21st century (probably in the second half). Its greatest virtue – apart from being free, inexhaustible, universally available and pollution-free – is that it can be converted directly into electricity, unlike any other energy source. Its potential, its current status and the challenges lying ahead are discussed next.

Solar Energy Balance

More than 99.9% of the energy flow on the earth's surface is due to incoming solar radiation. The rest is from geothermal, gravitational (tidal) and nuclear sources. The sun is an average-size star, with a diameter of 864,000 miles and 93 million miles away from our planet. It is a giant nuclear fusion reactor whose interior and surface temperatures are 35,000,000 and 10,000 °F, respectively. Each second 657 million tons of hydrogen isotopes are converted into 653 million tons of helium. The residual mass of 4 million tons is converted to energy, according to the Einstein equation, $E = mc^2$:

$$\text{Power from the sun} = (4\text{x}10^9\ \frac{\text{kg}}{\text{s}})\ (3\text{x}10^8\ \frac{\text{m}}{\text{s}})^2 = 3.6\text{x}10^{26}\ \text{W}$$

To place this number into perspective, if gasoline were pouring from Niagara Falls, at a rate of 5 billion gallons per hour, and if we had begun collecting it 3.5 million years ago, the combustion of all this accumulated gasoline would liberate the amount of energy equivalent to one minute of the sun's production. The reader is urged to verify this.

Being quite far away from the sun, the earth receives only about half a billionth of this radiation. But it receives it more or less continuously. About 30% of this energy does not reach the surface of the earth because it is reflected from the atmosphere (as ultraviolet radiation, see Figures 3-1 and 11-7). Still, the radiation that does reach the surface is four orders of magnitude larger than the total world's energy consumption (see Illustration 5-1 and Figure 5-2). In fact, only 40 minutes of sunshine would be sufficient – if available in adequate forms – to supply the entire annual energy demand on earth.

The *if* mentioned in the previous sentence is a big one, however. Because solar energy spreads out more or less evenly through space, it reaches the surface of the earth in quite diluted form, at a rate of about 220 W/m^2 (see Figure 3-1). In other words, if one square meter were available for conversion of solar energy to electricity (at 100% efficiency), the energy produced would be sufficient for just two or three light bulbs. The challenge of solar energy utilization is to concentrate it. Practical ways to achieve this are discussed below. They include direct solar heating, indirect production of electricity and direct production of electricity.

Direct Solar Heating

The use of solar rays to achieve effective heating has been practiced since ancient times. In 213 B.C., the Greek savant Archimedes used mirrors to direct sunlight onto the fleet of Marcellus, the Roman general who tried to capture Syracuse (Sicily), and set his ships on fire. Today's devices are not necessarily more sophisticated than the ones used by Archimedes. They are called *collectors*. A collector is thus a device that collects solar radiation and converts it to thermal energy.

Figure 17-1 shows the statistics of most recent shipments of solar collectors in the U.S. The low-temperature collectors are used primarily for less demanding residential consumption (to heat swimming pools, for example); it is good to see that their sales are up again. The medium-temperature collectors are used primarily for residential hot water. Both kinds became popular in the decade of the oil crises (1970s). However, consumer interest in them decreased sharply when the price of oil decreased in the 1980s (see Chapter 20) and when Federal solar energy tax credits expired in 1985.

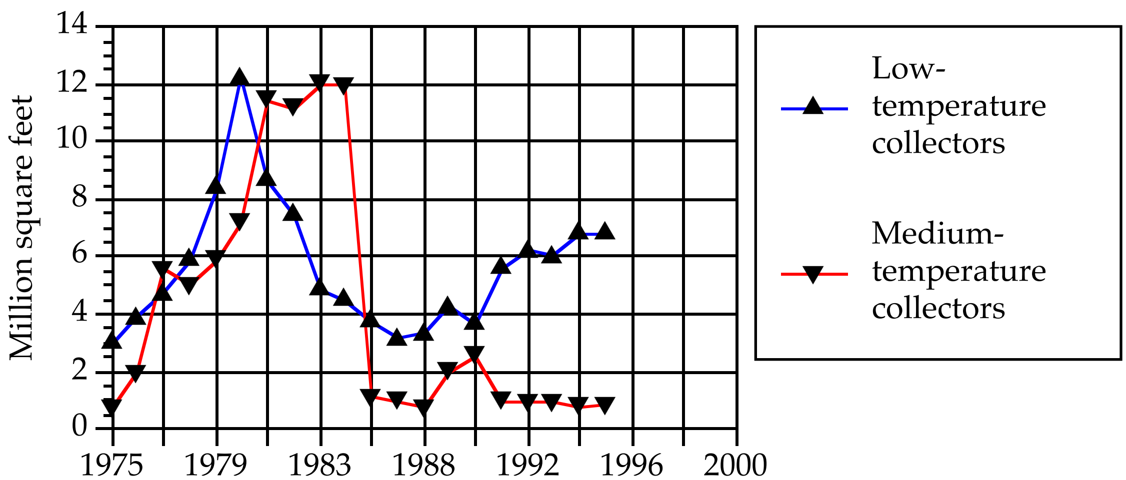

FIGURE 17-1. Shipment of solar collectors in the U.S. [Source: Energy Information Administration.]

Figure 17-2 is a schematic representation of a typical flat-plate collector used for domestic heating. A “working fluid” (such as air, water, oil or antifreeze) circulates through the tubes. The enclosure, with its black metal surface between the tubes and insulation at the bottom, is designed to maximize the absorption of solar radiation and its conversion to heat: the glass cover provides the greenhouse effect. The efficiency of conversion of solar radiation to heat stored in the working fluid is a complex issue; it is quite dependent on collector design. Man-made collectors are much less efficient than “natural collectors,” that is, animal furs. The fur of polar bears, for example, has been reported to have an efficiency of about 95%; no wonder they enjoy swimming in the icy Arctic waters! The most sophisticated, and most expensive, solar collectors have maximum efficiencies in the 65-70% range. Typical values on a cold winter day, when they are most used, are around 20%.

FIGURE 17-2. Schematic representation of a flat-plate collector.
[From “Energy and Problems of a Technical Society,” by J.J. Kraushaar and R.A. Ristinen. Copyright © 1988 by John Wiley & Sons. Reproduced with permission.]

In addition to the collector and the working fluid, a complete *active solar system* must have an energy storage facility and/or a backup system, because the sun does not shine all the time and it may not shine every day. Such a system is illustrated in Figure 17-3. The hot working fluid (such as antifreeze) exchanges heat with water in the primary loop, similar to the primary loop of a pressurized water nuclear reactor (see Figure 13-8). In the secondary loop, this hot water is used to heat the storage tank, from which the hot water is distributed to the various consumers (for example, a shower in a home or a dishwasher). The size of the storage system depends on the amount of solar energy incident on the collector and on the efficiency of the collector. This is shown in Illustration 17-1, based on the information given in Table 17-1.

In addition to the active solar energy system, *passive* solar heating system can be used effectively to reduce the heating (and cooling) requirements of houses and buildings. A passive system contains no active components, such as collectors and pumps; it relies on both regular and special features of building design. Walls, ceilings and floors constitute both the collection and the storage system. Heat is distributed by natural convection. Building design is optimized to let the sun in and keep it in in the winter, and to do the opposite in the summer. There are two ways to accomplish this: using the so-called *direct gain* and *indirect gain*.

FIGURE 17-3. Schematic representation of a solar energy storage system.

Illustration 17-1. A home in Phoenix (Arizona) requires 62 kWh of heat on a winter day to maintain a constant indoor temperature of 20 °C. (a) How much collector surface area does it need for an all-solar heating system that has a 20% efficiency? (b) How large does the storage tank have to be to provide this much energy?

Solution.
Phoenix is located at about 33 °N, so we can use the data for 32 °N given in Table 17-1. The average solar radiation in winter is about 6.5 kWh/m^2/day. Hence, the daily quantity of thermal energy obtained using collectors will be:

$$\text{Thermal energy} = 6.5 \frac{[\text{kWh (solar)}]}{\text{m}^2 \text{ day}} \frac{[0.20 \text{ kWh (thermal)}]}{[1 \text{ kWh (solar)}]} = 1.3 \frac{\text{kWh}}{\text{m}^2 \text{ day}}$$

This means that for every square meter of collector surface area, 1.3 kWh of heat are produced every day. Therefore, the required collector surface area is obtained as follows:

$$\text{Collector surface area} = \frac{62 \frac{\text{kWh}}{\text{day}}}{1.3 \frac{\text{kWh}}{\text{m}^2 \text{ day}}} = 48 \text{ m}^2$$

So a collector 6 m long and 8 m wide would do the job. Obviously, it can be placed on the roof. The size of the storage tank can be obtained by remembering the quantitative definition of heat (Chapter 3):

Heat = [Mass] [Heat capacity] [Temperature difference]

Here the mass is that of the storage medium, water, which needs to be determined. The heat capacity of water is 1 kcal/kg/°C (see Table 3-2), and the temperature difference is that between the hot fluid in the secondary loop and the cold water going into the storage tank (say, 60 – 20 = 40 °C); see Figure 17-4. Therefore, the required mass of water for a day's worth of heat is obtained as follows:

$$\text{Mass} = \frac{\text{Heat}}{[\text{Heat capacity}]\,[\text{Temperature difference}]} =$$

$$= \frac{62 \text{ kWh}}{\left(1 \frac{\text{kcal}}{\text{kg °C}}\right)(40 \text{ °C})\left(\frac{1.16\text{x}10^{-3} \text{ kWh}}{1 \text{ kcal}}\right)} = 1336 \text{ kg } H_2O$$

This is equivalent to a volume of 1336 liters (or about 350 gallons), because the density of water is 1 kg/L.

TABLE 17-1
Variation of solar radiation (in W h/m^2) with time and latitude

Date	Perpendicular	Horizontal	Vertical South	60° South
October 21				
32°N	8,498	5,213		
40 °N	7,735	4,249	5,212	6,536
48 °N	6,789	3,221		
November 21				
32 °N	7,584	4,035		
40 °N	6,707	2,969	5,314	6,013
48 °N	5,257	1,879		
December 21				
32 °N	7,401	3,581		
40 °N	6,235	2,465	5,188	5,660
48 °N	4,551	1,406		
January 21				
32 °N	7,748	4,060		
40 °N	6,878	2,988	5,440	6,127
48 °N	5,390	1,879		
February 21				
32 °N	9,053	5,434		
40 °N	8,321	4,457	5,452	6,858
48 °N	7,344	3,404		
March 21				
32 °N	9,494	6,569		
40 °N	9,191	5,838	4,677	6,852
48 °N	8,763	4,974		

[Sources: Kraushaar and Ristinen, op. cit.; A.W. Culp, Jr., “Principles of Energy Conversion,” McGraw-Hill, 1991.]

Direct gain refers to systems that admit sunlight directly into the space requiring heat. The maximum reception of sunlight is obtained through windows facing south, as shown in Figure 17-4 (see also Table 17-1). The sunlight received during the day – while it lasts – must be absorbed by a high-heat-capacity material on the floor or the walls. As shown in Table 3-2, dense substances such as concrete, brick, stone, adobe and water can store relatively large quantities of heat in a reasonable amount of space. When the sun ceases to shine, the warm floor and walls transfer the accumulated heat to the cold space in the house.

Indirect-gain passive systems are those that also absorb solar radiation in a high-heat-capacity material, such as an outside concrete wall. The accumulated thermal energy is then transferred to the space needing heat. The south-facing *Trombe wall*, named after the French engineer Félix Trombe, is the most commonly used passive solar structure. It is built of concrete, brick or stone; it can even be filled with water. It is often painted black for maximum absorption of radiation. This increases its efficiency but does not help to embellish the neighborhood; there are regulations in some residential areas that do not allow these structures on the street-facing side of the house. An alternative system is a *roof pond*: water is contained in large, shallow bags between the ceiling and the roof. Movable insulating material separates it from the roof. During the day, insulation is removed to allow sunlight to strike the pond; during the night, it is placed back in its position so that it allows the heat to be transferred mostly toward the inside of the house.

The most familiar example of a passive solar system is the *greenhouse*, also called sunspace or sunporch. It is used both for growing plants and for residential comfort in winter. It combines direct and indirect gain, by letting the sunshine into the room through south-facing glass and absorbing the radiation on a brick wall inside the room. (This is the origin of the term “greenhouse effect,” discussed in Chapter 11.)

FIGURE 17-4. Solar heat gain for different window orientations.
[Source: G. Aubrecht, op. cit.]

In the ruins of ancient civilizations, there are numerous examples of very effective passive solar heating and cooling systems. The ancient cliff dwellings in the Mesa Verde National Park in Colorado are a familiar example. As the cost of heating and cooling increases in our days, architects, home owners and builders are wise in remembering these examples and adapting them to current building materials and lifestyles. It is well documented that they can provide significant energy savings.

Indirect Production of Electricity

The use of a more sophisticated collector system – compared to the one represented in Figures 17-3 and 17-4 – allows the working fluid to achieve a higher temperature. Such a system can then be used to produce electricity. This is illustrated in Figure 17-5. A solar thermal power plant is essentially identical to an ordinary steam-turbine power plant, except that it gets the heat from solar radiation rather than from combustion or nuclear fission.

FIGURE 17-5. Schematic representation of a solar thermal power generation plant.

A flat-plate collector typically raises the temperature of the working fluid to about 100 °C. A number of flat-plate collectors placed in series can raise the temperature of the working fluid to levels that can provide economically competitive electricity. For example, the maximum efficiency of the turbine of a power plant whose entering steam temperature is 200 °C would be

$$E_{max} = \frac{T_H - T_L}{T_H} = \frac{(200 + 273) - (100 + 273)}{(200 + 273)} = 0.21$$

This is a low efficiency, but the 'fuel' (solar energy) is free. A higher temperature can be achieved by using concentrating, or focusing, collectors – as Archimedes did to burn Roman ships. With the use of parabolic trough collectors, for example, steam temperatures of up to 300-400 °C can be reached. This technology is currently cost-competitive in certain markets. In the Mojave desert (Kramer Junction, CA), Luz International has built a plant that delivers 354 MW of electricity to Southern California Edison's power grid (see Investigation 17-1).

Temperatures as high as those in conventional power plants can be achieved easily with solar tower technology. Here, a system of computer-controlled mirrors (called heliostats) tracks the sun across the sky so that the reflected sunlight from all the mirrors falls on a central tower containing water or oil or, in more recent designs, a molten salt. At Barstow, California, some 1900 heliostats were used to raise the temperature of water to 510 °C and the 10 MW(e) Solar One plant had an overall efficiency comparable to that of conventional power plants. And the new 10-MW(e) Solar Two at the same location is advertised today as the world's most technically advanced solar power plant. It uses a molten salt as the heat transfer fluid. The advantage is that the thermal energy collected during sunny hours can be stored in the molten salt (see Illustration 17-2) and used on cloudy days or at night. If successful, it will pave the way for a new generation of commercial power plants.

Illustration 17-2. How much less heat storage medium would be needed in Illustration 17-1 if a molten salt were used instead of water? Because it undergoes a phase change (from solid to liquid), the amount of heat that can be stored in the salt is larger, say 120 BTU/lb, than the amount that can be stored in water.

Solution.
The mass of molten salt required is

$$\text{Mass} = \frac{\text{Heat}}{[\text{Heat capacity}]\ [\text{Temperature difference}]} = \frac{(62\ \text{kWh})\ (\frac{3414\ \text{BTU}}{1\ \text{kWh}})}{120\ \frac{\text{BTU}}{\text{lb}}} = 1764\ \text{lb}$$

Compare this to almost 3000 pounds of water needed for the same heat storage task.

The Department of Energy reports that annual shipments of these high-temperature collectors were less that 5 thousand square feet in 1994, down from 5.24 million square feet in 1990. Clearly, non-electric use of low- and medium-temperature solar collectors is more popular at the present time (see Figure 17-1).

Direct Production of Electricity

Indirect production of electricity from solar energy, while quite promising because of recent significant progress in technology and in economic competitiveness (see Chapter 18), has two major drawbacks. Because of its relatively low efficiency (especially using flat-plate-collector systems), the size of the proposed *solar farms* can be very large. This is illustrated below.

Illustration 17-3. How much collector area would a 1000-MW(e) solar farm require if the individual efficiencies of the collector system, turbine and generator are 30, 25 and 90%, respectively?

Solution.
Let us assume that the average incident solar radiation at the proposed site of the plant is 200 W(solar)/m^2. This means that 1 m^2 of earth's surface receives 200 W of solar radiation. If a collector is placed on this surface, it will convert 30% of this energy into heat; therefore for every square meter of collector, 60 W of thermal energy will be available. Now, taking into account the efficiencies of the turbine and the generator, we have that the collector area required is:

$$\text{Collector area} = \left(\frac{1\ \text{m}^2}{60\ \text{W(th)}}\right)\left(\frac{1\ \text{W(th)}}{0.25\ \text{W(m)}}\right)\left(\frac{1\ \text{W(m)}}{0.9\ \text{W(e)}}\right)\left(10^9\ \text{W(e)}\right) = 7.4\text{x}10^7\ \text{m}^2$$

Thus, with the efficiencies given above, this solar farm would occupy an area of about 75 square kilometers. If land is expensive, this would represent a significant capital investment.

Direct conversion of solar energy to electricity would not only avoid this problem, but would avoid the "thermodynamic bottleneck" illustrated in Figure 17-6, which none of the technologies mentioned so far are capable of doing. In most of our discussion of electricity generation so far, the energy conversion path has been the one shown in the upper portion of Figure 17-6.

The direct conversion of chemical energy to electricity is possible in devices called *fuel cells*. These are a type of large-scale batteries that have been used for decades in the NASA space programs. In contrast to ordinary batteries, however, fuel cells require a continuous supply of chemical energy (from natural gas, for example) and the electrode material is not depleted as it supplies electricity. Their commercial use in power plants and electric transportation is increasingly being considered, particularly in densely populated areas (because of their very low environmental emissions and silent operation). A 4.8 MW(e) demonstration plant had been operational in downtown Manhattan since the early eighties. A number of utility companies across the U.S. have purchased 2 MW(e) plants, one of them to power the New York City subway system (*The New York Times*, June 30, 1991, p. F6). More recently, a 2 MW(e) plant that is considered to be simpler and more efficient than many other types of fuel cell power plants was connected to the grid of the Santa Clara municipal electric system. (For an update on this Santa Clara demonstration project, see www.ercc.com/scdp.html. For an update on fuel cell technology in general, visit the Web site of the Morgantown Energy Technology Center of the Department of Energy, www.metc.doe.gov.)

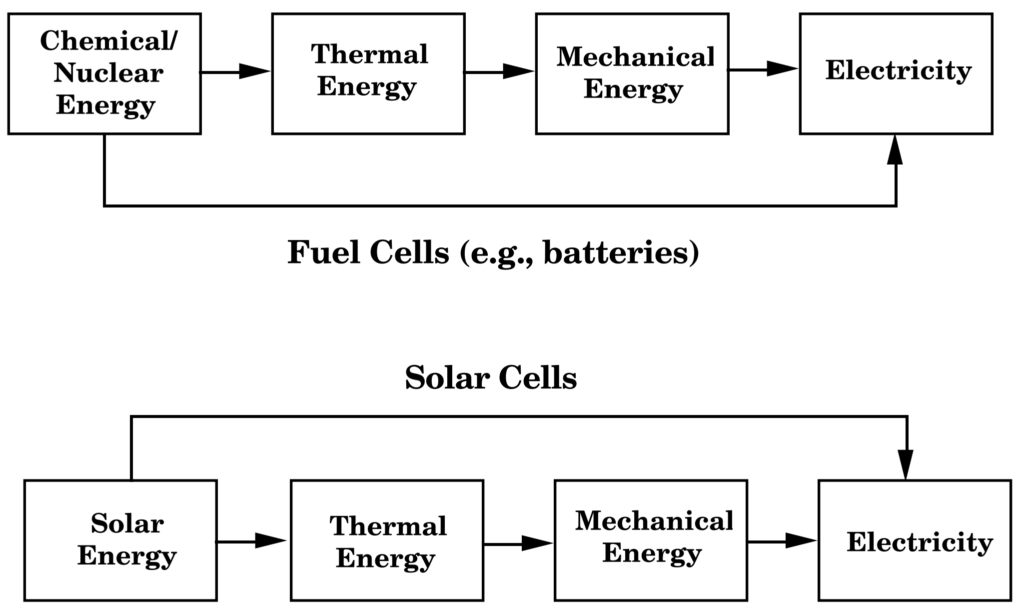

FIGURE 17-6. Energy conversion pathways of fuel cells and solar cells.

Like fuel cells, *solar cells* produce electricity directly, without going through the thermodynamically unfavorable conversion of high-entropy thermal energy into low-entropy mechanical energy (remember Chapter 3). Therefore, in theory at least, the efficiency of this conversion could be as high as 100% and this – together with the fact that solar energy is free, inexhaustible and nonpolluting – provides great incentive to develop this new technology.

A solar cell, also called *photovoltaic cell*, is thus a device that directly converts solar radiation into electricity. It is based on the photoelectric (or photovoltaic) effect, which was known since the early 19th century, but which was translated into a useful device only in the 1950s, in response to the needs of the U.S. space program. This effect, exhibited by materials called *semiconductors* (such as silicon), is illustrated in Figure 17-7. Transistors and computer chips, which have revolutionized the electronics industry since the 1940s, are also made from semiconducting materials.

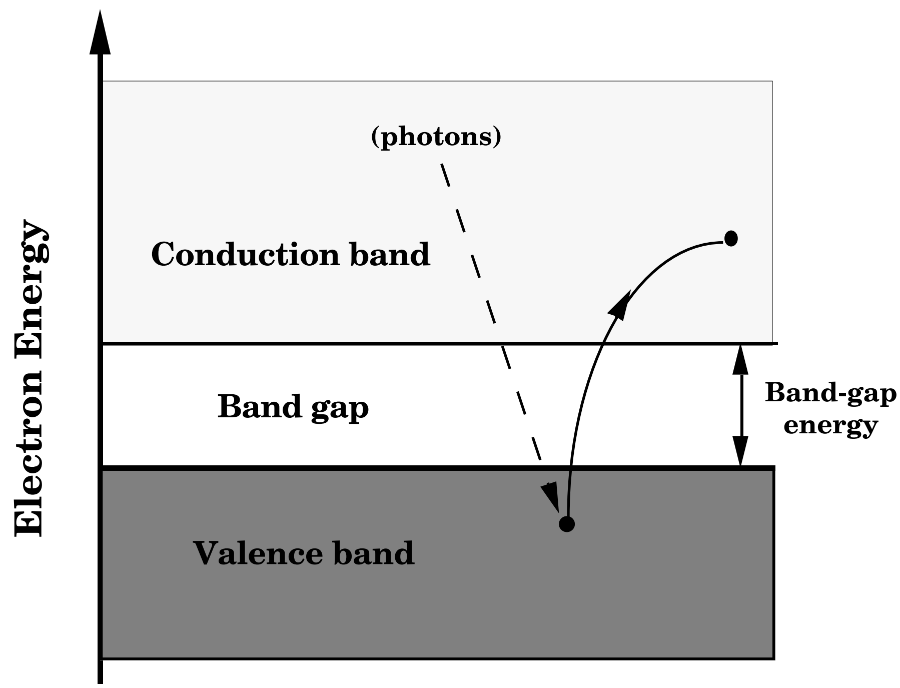

FIGURE 17-7. Photovoltaic effect in semiconductors.

The electrons that have the potential to create an electric current are normally tied up in their valence band, that is, at a low energy level. An energy barrier (called the band-gap energy) must be overcome before they can become carriers of electricity in this material, by jumping into the so-called conduction band. Solar radiation, in the form of elementary particles called photons, provides the needed energy; the photons strike the surface of the semiconductor and some of the valence electrons are ejected into the conduction band. They are thus made free or available for *conduction* of electricity. But for the *production* of electricity, the actual solar cell device must be made from two different types of so-called ’doped’ semiconductors. This is shown in Figures 17-8 and 17-9 and described below.

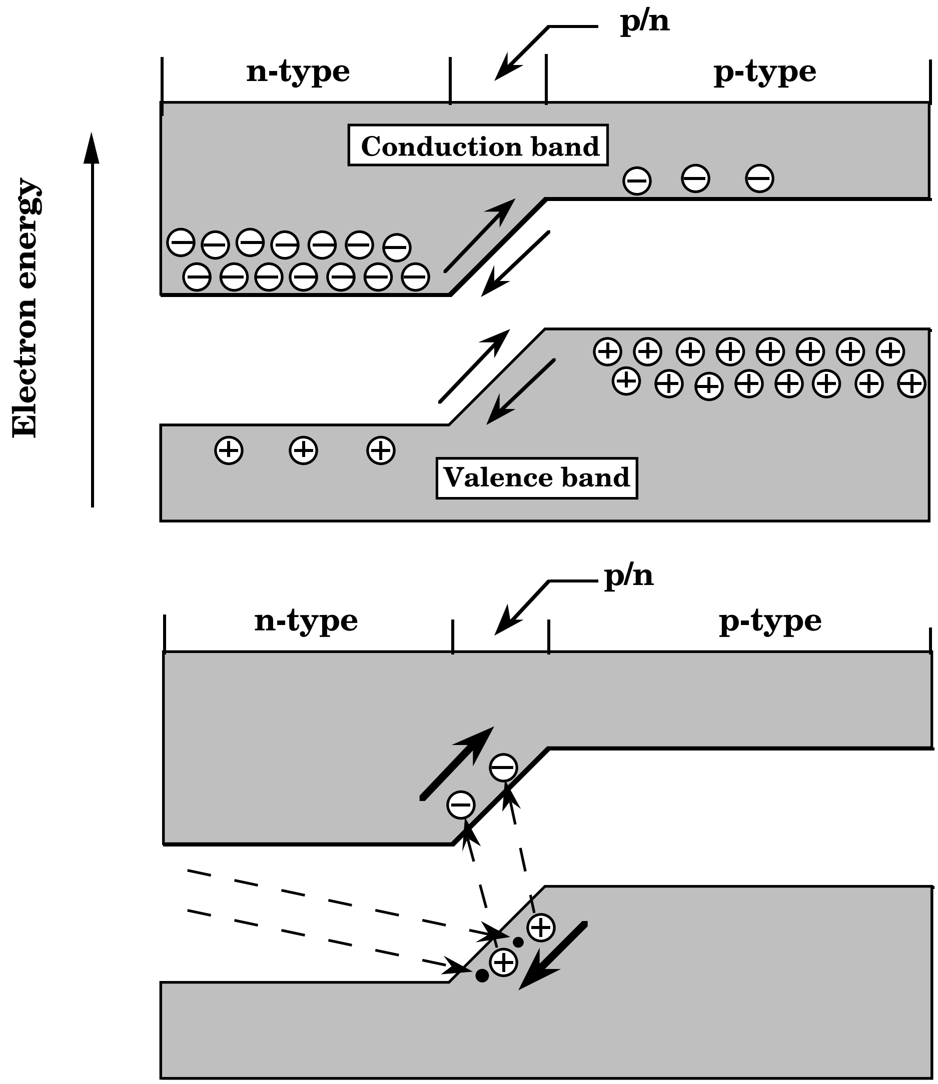

FIGURE 17-8. The charge distribution in the p/n junction region of a solar cell: (a) without solar radiation; (b) with solar radiation.

In a normal silicon crystal, there are four valence electrons in every atom. They are held in place by the positive charge from the nuclei of the silicon atoms. They easily come back to the valence band before they can give up their energy in an external electric circuit. However, if the silicon is doped with a small quantity of an element that has five valence electrons and can fit into the silicon crystal structure (such as phosphorus or arsenic), some extra electrons are created. Such a doped material is called an *n-type semiconductor*, because the extra electrons carry a *negative* charge. Alternatively, if the semiconductor is doped with an element that has only three valence electrons (such as boron or gallium), instead of creating extra electrons, extra missing electrons, or *positive* holes, are created. This is a *p-type semiconductor*. Still, both materials are electrically neutral when they are separated: in the n-type material the negative charge of the extra electrons is balanced by the higher positive charge of the dopant nuclei (e.g., phosphorus), and in the p-type material the extra electron holes are balanced by the lower positive charge of the dopant nuclei (e.g., boron).

When these two types of material are combined, a p/n junction is formed. This is what makes possible the production of electricity, as opposed to simple conduction of electricity in a semiconductor illuminated by solar radiation. Because of the high concentration of electrons in the n-type semiconductor, some of the extra electrons spill over into the holes of the p-type semiconductor. This makes the n-type material positively charged in the vicinity of the junction. Conversely, the p-type material becomes negatively charged in the vicinity of the junction. An (internal) electric field across the junction is thus created. Normally, however, there is equal flow of electrons in both directions across the junction (Figure 17-8a) and no electricity can be produced.

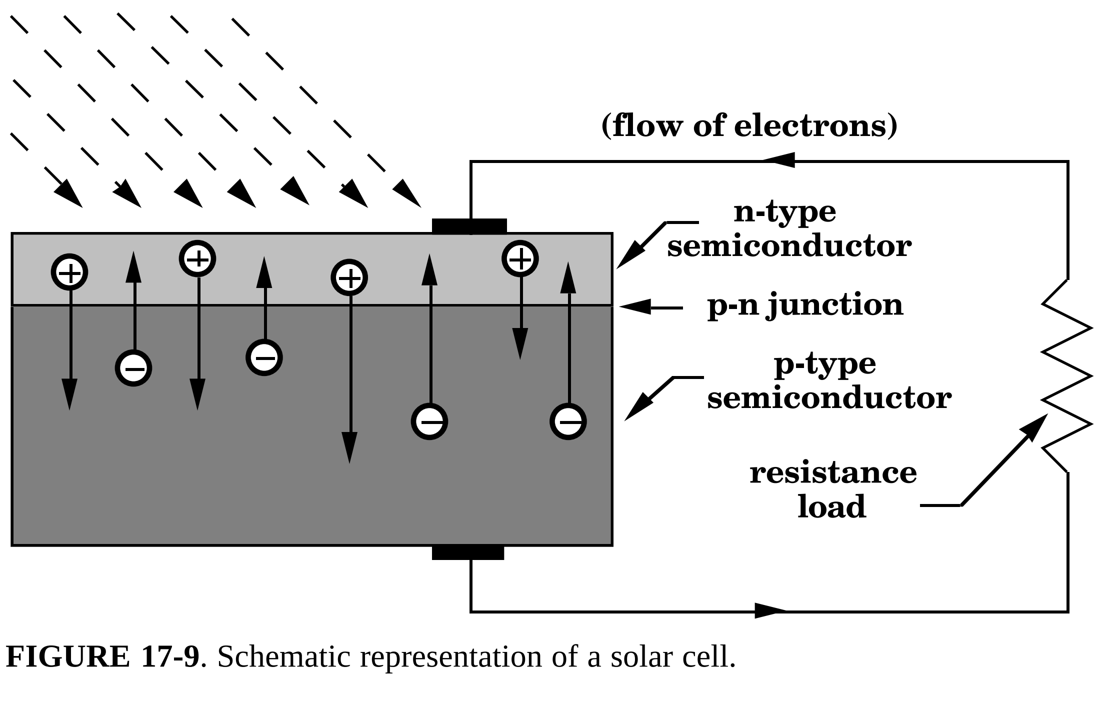

FIGURE 17-9. Schematic representation of a solar cell.

When solar radiation strikes the solar cell (Figure 17-8b), excess electrons flow from the n-type material to the p-type material and excess holes ‘flow’ in the opposite direction. This, together with the existence of the electric field across the junction, makes possible the flow of electrons away from the (charge-separating) junction and through an *external* circuit (Figure 17-9). Thus, solar energy is converted into electricity.

Figures 17-10 and 17-11 summarize the growth of the photovoltaic-cell market in the U.S. and the world. The contribution to the overall energy supply is still low (see Chapters 5 and 18) but the growth has been phenomenal. It has occurred mostly in the developed nations (U.S., Japan, Europe). The growth in the U.S. has been most significant in the residential sector. Developing nations (such as Brazil, India, and China) have also contributed to the worldwide growth, because one of the key advantages of the photovoltaic technology is its rural applicability, in remote areas lacking access to central power supplies. The cumulative world capacity now approaches 600 MW. It is mostly used for on-peak consumption (see Chapter 18). It must be concluded, however, that both economic and efficiency problems still stand in the way of large-scale commercial utilization of this technology.

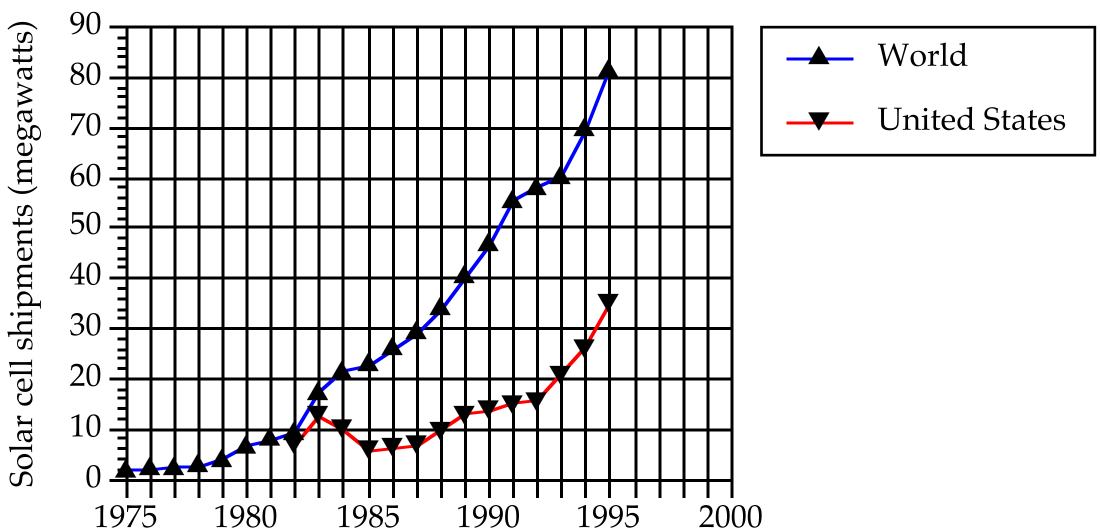

FIGURE 17-10. Use of solar cells in the U.S. and the world in the past two decades. [Source: *Vital Signs 1996*, Worldwatch Institute, and Energy Information Administration.]

Every new incremental increase in the efficiency of a solar cell attracts a great deal of attention in the popular press. While there are no thermodynamic limitations, as mentioned above, there are inherent energy losses that severely limit the performance of currently available cells. These include optical losses (for example, reflection of the radiation from the cell's surface, before reaching the p-n junction) and the (more serious) inability of the currently designed cells to provide for the conversion of the entire sunlight spectrum (see Figure 2-2) into electricity. Despite these limitations, the efficiency of an individual solar cell has increased from 5% in the early designs to about 35% in the most advanced designs.

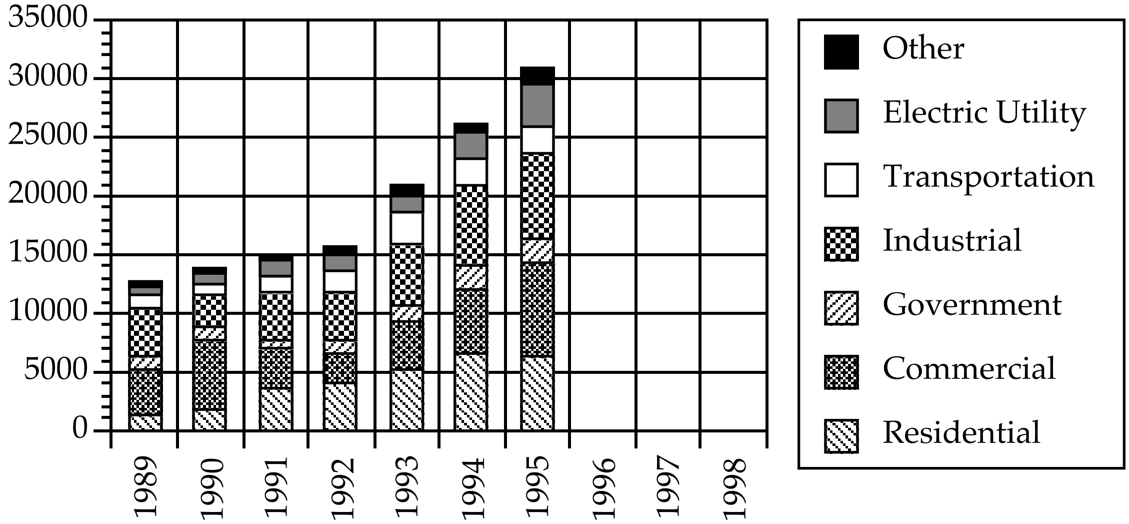

FIGURE 17-11. U. S. photovoltaic energy contribution by economic sector (in kilowatts purchased). [Source: Energy Information Administration.]

More important than the issue of efficiency is the cost issue – after all, solar energy comes for free – and here dramatic changes have taken place. This is illustrated in Figure 17-12. In *Vital Signs 1996*, the Worldwatch Institute reports no additional decrease in the price of solar electricity; today solar cells cost $3.50-4.00 per watt. In a recent NYT article ("70's Dreams, 90's Realities. Renewable Energy: A Luxury Now. A Necessity Later?," 4/11/95), the following costs for a kilowatthour of electricity are given:

Natural gas	3 cents
Wind	5 cents
Geothermal	5.5 cents
Solar (thermal)	14 cents

A similar summary was published in a May 1994 issue of *Business Week* ("The sun shines brighter on alternative energy"):

Coal	4-5 cents
Natural gas	4-5 cents
Wind	5-9 cents
Geothermal	5-8 cents

Hydropower	4-7 cents
Biomass	6-8 cents
Solar (thermal)	10-12 cents
Photovoltaic	30-40 cents

(Environmental benefits of solar energy may not have been factored into these prices; see Chapter 21.) In these circumstances, some companies in the U.S. have abandoned solar energy, unsure of when they will be able to convert it into electricity with a profit (see "U.S. Companies Losing Interest in Solar Energy," in the NYT of 3/7/89; see also Investigation 17-1). Others are using cheaper but lower-efficiency materials (thin films of amorphous silicon) and are still working on efficiency improvements.

During the Bush Administration, the Department of Energy had anticipated (in its *National Energy Strategy*) that utility-scale applications of photovoltaics will reach commercial level around the year 2015. Current official projections do not seem to be as optimistic. In the *Sustainable Energy Strategy*, the statement about DOE's Photovoltaics System Program is more vague when it comes to commercial-scale utilization: "[This] Program supports private sector research to develop roofing materials and windows that incorporate photovoltaics and can produce electricity. These efforts are pursued in close collaboration with industry in programs with the Utility PV Group."

Finally, photovoltaic technology is expected to bring closer to reality the use of hydrogen as an energy source. The concept is illustrated in Figure 17-13. It is a sun-assisted water cycle. Solar radiation is converted to electricity, which is then used to break up water into hydrogen (H_2) and oxygen (O_2). Hydrogen is then used as a clean gaseous fuel, whose combustion regenerates water, produces a lot of energy (274 BTU/ft^3) and causes no pollution. But don't expect to see this wonderful technology at your local electric utility any time soon (in your lifetime, I mean).

INTERNET INFO	For the most recent developments in solar energy and other renewable energy sources, visit the following Internet sites: •www.nrel.gov; •www.eren.doe.gov/RE/solar.html •solstice.crest.org •www.energy.ca.gov/education/index.html •www.crest.org/renewables/usecre// •www.ises.org/

FIGURE 17-12. History and projections of solar electricity costs.
[Sources: C.J. Weinberg and R.H. Williams, "Energy from the Sun," *Scientific American*, September 1990, p. 154.]

FIGURE 17-13. Conceptual scheme of the use of solar cells to produce hydrogen.

REVIEW QUESTIONS

17-1. Show the origin of the numbers quoted at the beginning of this chapter from the *Sustainable Energy Strategy*.

17-2. On p. 314 it is stated that only 40 minutes of sunshine would be sufficient to supply the entire annual energy demand on earth. Show where this number comes from.

17-3. It has been reported that the latest module of the SEGS (solar electric generating system) plant in Kramer Junction, CA generates 80 MW of electricity by using 483,360 square meters of collectors to achieve an annual output of 260 gigawatthours. Check whether these numbers make sense. What is the efficiency of the collectors?

17-4. In 1994 the Spanish *El País* has reported on the largest photovoltaic power plant in Europe, near the city of Toledo. Its electric capacity is 1 MW (enough for 2000 people, the paper says), and the total area of the solar panels is reported to be 16,700 square meters. Do these numbers make sense? What is the efficiency of these solar cells?

17-5. Indicate whether the following statements are true or false:
(a) A solar cells converts solar radiation directly into electricity.
(b) A window in New York City that is facing south receives as much as three times more solar radiation than a window facing north.
(c) From 1980 to 1983 the sales of medium-temperature solar collectors exceeded the sales of low-temperature solar collectors.
(d) In 1995 U.S. sales of photovoltaic cells represented less than 50% of world sales.
(e) In 1983 U.S. sales of photovoltaic cells represented less than 50% of world sales.
(f) The principal customers for the photovoltaics industry are the electric utilities.
(g) In 1990 more than 50% of the photovoltaics have been sold to the residential and commercial sectors.

INVESTIGATIONS

17-1. It may be difficult to keep up with all the technical, economic and political developments in solar energy. The Internet is the ideal tool to try to accomplish this, but distinguishing facts from both fiction and propaganda may be time-consuming. Spend some time surfing the Internet to find out about the current status of the SEGS plant in Kramer Junction, CA and about the company that has pioneered this technology, Luz International. Use at least two search engines and check at least three different Web sites.

17-2. Use of photovoltaics in rural areas may already be cost-competitive with conventional technologies. See why it makes sense in South Africa (“Solar power: Night and day,” *Economist* of 9/9/95) and elsewhere in the developing world (“Here Comes the Sun,” *Time* of 10/18/93, and “A Sunny Forecast,” 11/7/94; and “America Unplugged,” *Newsweek* of 10/18/93).

17-3. The following companies have been reported to be involved (in May 1994) in developing photovoltaic technology: Siemens Solar Industries, Solar Engineering Applications, United Solar Systems, Canon USA, Alpha Solarco, Solarex, Bechtel Power, Mobil Solar Energy, Amonix, Ascension Technology, Cummins Engineering, Scientific Analysis, Fresnel Optics, Texas Instruments, Integrated Power and SunPower. See whether they have Web sites. How many of them are still in the business? Maybe you'll even want to invest in some of them...

17-4. The Enron Corporation has been known as a natural gas company (see Investigation 9-6). But they were (and still are?) also interested in photovoltaics (“Solar Power, for Earthly Prices,” NYT of 11/15/94). Find out about the fate of their pledge “to deliver the electricity at 5.5 cents a kilowatthour in about two years.” See also NYT of 12/4/94 (“Thirsty New Solar Cells Drink In the Sun's Energy”).

17-5. Find out more about the direct conversion of chemical energy to electricity accomplished by fuel cells. See BW of 5/27/96 (“How To Build a Clean Machine: Fuel cells are powering hospitals. Cars are down the road.”) and *Economist* of 2/5/94 (“The different engine: Fuel cells are efficient, clean and quiet. So why are they also rare?”)

17-6. Find out more about the possibilities of using gaseous hydrogen (H_2) as a fuel. See NYT of 4/16/95 (“Use of Hydrogen as Fuel Is Moving Closer to Reality”). See also *Popular Science* of 10/93 (“The Outlook for Hydrogen”).