

# Future Energy: Opportunities and Challenges

## Part II. Energy Sources

### Chapter 6. Solar Energy

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# **Future Energy:** Opportunities and Challenges

Thomas W. Kerlin



**6**

# **Solar Energy**



## The Main Points

- Photon absorption heats an absorber, causing it to emit photons (called *re-emitted photons*).
- Solar heating involves the use of a collector to capture solar photons and re-emitted photons produced within the collector.
- Capture of re-emitted photons in a collector involves the use of a window that transmits solar photons, but absorbs re-emitted photons.
- Solar electricity may be produced using photovoltaic systems or solar heat engines.
- The photoelectric effect involves release of electrons upon absorption of photons.
- Solar heat engines use mirrors or lenses to focus solar photons to provide a high temperature energy source for the engine.

## 6.1 Introduction

The solar energy resource described in the previous chapter may be used for heating or cooling applications or for producing electricity. Solar energy is attractive because it is there for the taking. But the use of solar energy requires consideration of two main issues: How much solar energy can be captured in a practical and economical way? How can the intermittency of solar energy be accommodated?

Three appendices (G, H, and I) augment this chapter with detailed information related to the practical application of solar energy. Two other appendices (J and K) contain related information about radiation absorption physics and vapor absorption refrigeration (which can be powered by solar radiation).

## 6.2 Solar Heating

### 6.2.1 Principles

Solar collectors for heating applications may be glazed (with a glass or plastic cover) or unglazed. Unglazed systems are used for low-temperature applications and are less efficient and less expensive than glazed systems.

For glazed systems, solar heating involves admitting sunlight through a glass or plastic cover into a closed space, absorbing incident radiation on a blackened collector floor and then absorbing re-emitted photons before they can escape to reach the atmosphere. Glass—and some clear plastics—readily transmit solar photons but absorb re-emitted photons. An enclosed structure with a transparent glass or plastic cover facing the sun and a blackened absorptive surface will capture solar energy. This heats the interior of the structure, and a liquid or gas that passes through the structure can carry the heat away. The use of such energy-trapping devices for applications such as space heating and water heating is growing.

Desirable features of glazed solar collectors are as follows:

- Strong absorption of incident photons that reach the heat deposition site (the black floor of the collector)
- Window with high transparency to incident photons
- Window with low transparency to re-emitted photons
- Insulation on sides and bottom to reduce heat losses
- Efficient heat transfer to a liquid or gas that carries the heat out of the collector

Solar heaters may be “active” or “passive.” Active collector designs use a pump or fan to circulate the heat transfer liquid or gas. Passive systems use

natural circulation (warmer fluid rises, and cooler fluid sinks) for circulation of the heat transfer fluid.

Solar collector designs include flat-plate collectors and evacuated tube collectors. Flat-plate collectors are simply boxes (usually rectangular) with a transparent window on top and a blackened surface on the inside bottom. Tubes along the inside bottom contain a liquid or gas that carries the heat away. Figure 6-1 shows a flat-plate collector. Evacuated-tube collectors use glass tubes from which air has been evacuated and which contain blackened concentric tubes for liquid circulation. The vacuum minimizes heat losses from the tubes to the surrounding air. Figure 6-2 shows a typical evacuated-tube collector.

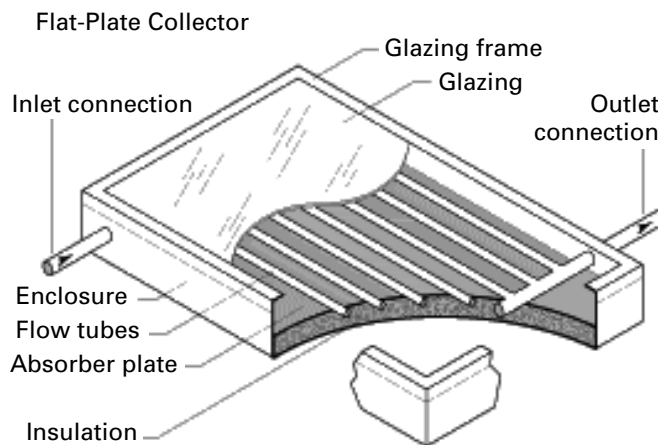


Figure 6-1. A Flat-Plate Solar Collector (courtesy of U.S. Dept. of Energy)

A common installation site is on rooftops, especially for residential applications (see Figure 6-3). A wide array of solar collectors is available from vendors, and many designs are available for do-it-yourself projects.

### 6.2.2 Residential Applications

Solar heating may be used in residences for water heating, space heating, and pool heating.

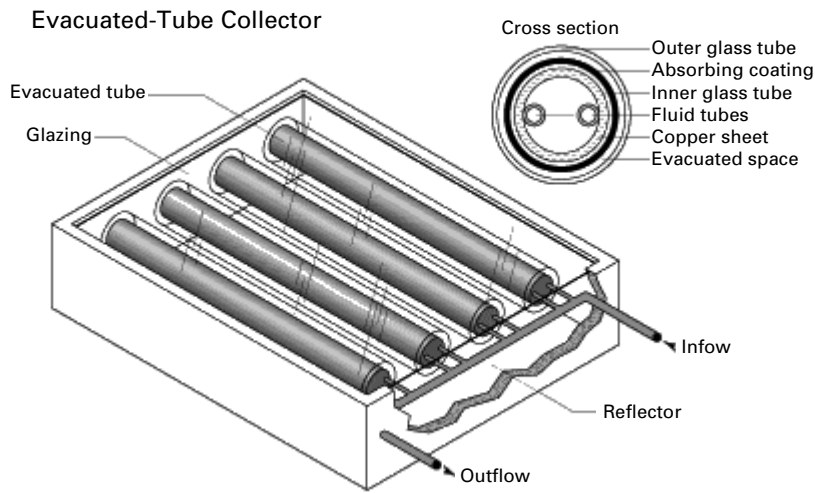


Figure 6-2. An Evacuated-Tube Solar Collector (courtesy of U.S. Dept. of Energy)



Figure 6-3. A Typical Roof-Top Solar Collector (courtesy of U.S. Dept. of Energy)

### *Water Heating*

Water heating system design requirements depend on hot water demand and on local solar radiation intensities. Water heating is needed in all homes, and the need is year-round. A solar water heating system that provides just enough hot water in summer would fall short in winter, and a system that provides just enough hot water in winter would have excess

capacity in summer. The property owner must decide which of these objectives will be the basis for selecting the collector design.

Collectors used for solar water heating systems are generally the glazed type and may be flat-plate collectors or evacuated tube collectors. The collector orientation in winter should be so as to maximize solar energy absorption. Changing the collector orientation in warmer months is needed only if maximizing energy capture in every season is beneficial.

As will be discussed in Chapter 15, the average American home uses about 100 million BTU of energy per year. Water heating accounts for about 17 percent of residential energy use, or 17 million BTU per year per household.

Unlike space heating energy requirements, water heating energy requirements do not depend on climate or the energy use characteristics of the residence such as size, insulation, number of doors and windows, shading, etc. Consequently, it is easier to estimate typical requirements for solar water heating systems than for space heating.

Determining the required size of a solar collector for water heating can be simple (and very approximate) or very detailed. The simplest, rule of thumb procedure provided by The U.S. Department of Energy<sup>1</sup> is as follows:



*Rule of Thumb: Provide 20 square feet of collector for each of the first two residents. Add 8 square feet for each additional resident for homes in the Sun Belt and 12 to 14 square feet for each additional resident for homes in the northern U.S.*

Detailed estimates for a specific location can be made by solar contractors or with software available to the public on the Internet. A search on “solar collector calculation” will provide numerous free calculation packages. These packages account for local conditions, and some also provide cost estimates.

The essence of collector sizing calculations is outlined in the following example:

**Example 6.1**

Consider a solar water heater for a home in Knoxville, Tennessee, with a water-heating energy requirement of 17 million BTU per year or 46,600 BTU per day. Figure 6-4 shows the radiation absorption for a two-axis tracking collector (the type that provides the greatest absorption per unit area) and a fixed orientation collector oriented at 50.82 degrees (latitude plus 15 degrees, a good winter orientation). (See Appendix H for details about collector orientation.)

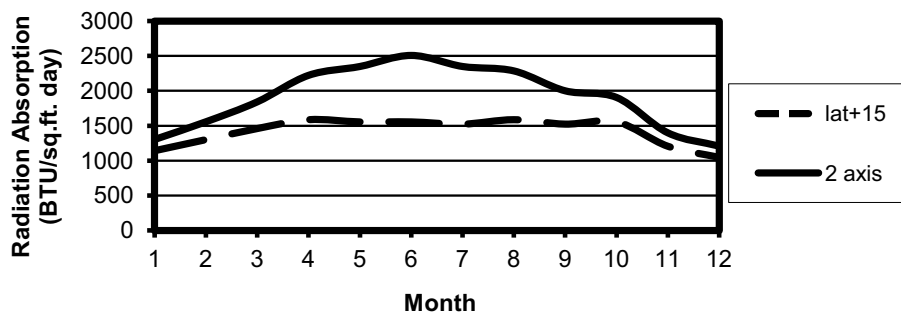


Figure 6-4. Knoxville Solar Radiation Absorption (horizontal collector)

The figure shows the radiation impinging on the fixed-axis collector varies from about 1050 BTU per square foot per day in winter to about 1550 BTU per square foot per day in mid-summer. The yearly average for the fixed-axis collector is about 1,425. For a two-axis tracking collector the range is from 1,200 in winter to 2,500 in summer. Significantly, the wintertime radiation is nearly the same for both types of collector. The yearly average for the two-axis tracking collector is about 1,900.

The figure shows the fixed-axis collector, sized for summer water heating, sees about 67 percent as much radiation in the middle of winter as it does in summer. The yearly average is about 92 percent of the maximum radiation seen by the collector.

*For a collection efficiency of 50 percent, a fixed-axis collector sized for summer water heating would need about 60 square feet of surface ( $46,600/(1,550 \times 0.5)$ ). Such a collector would provide 92 percent of annual water heating energy. Sizing the collector to provide 100 percent of annual water heating energy would result in significant excess capacity in the warmer months.*

*The two-axis collector would require less collector surface, but at the expense of a more complex design.*

*Note that the rule of thumb gives estimates of 48 square feet in the Sun Belt and 52 to 54 square feet in the northern U.S. for the average U.S. household (three people). Also, one of the on-line water heater energy calculators<sup>2</sup> gives a panel area requirement of 64.6 square feet for the Knoxville application. Clearly, all three estimation methods give comparable results.*

The collector is only one essential part of a solar water heating system. The system must also include plumbing, controls, storage, and, in colder regions, freeze protection. Solar water heaters are usually installed in series with a conventional water heater to ensure a hot water supply on overcast days.

### *Space Heating*

Solar space heating is similar to water heating, but with an important difference. Space heating is needed only in cooler months, but that is when solar radiation is weakest. Collector sizing must account for low winter solar energy availability. A backup heating system is usually provided to compensate for solar energy shortfalls. Backup heat or energy storage is also needed for nighttime heating.

The collectors are generally glazed and may be flat-plate or evacuated tube types.

Space heating is needed when the average outdoor temperature is lower than some level at which heating is needed for comfort. A common cutoff is an average outdoor temperature of 65°F (18°C). The duration of time with average monthly temperatures above 65°F ranges from no months per

year in the northern continental U.S. to 12 months per year in southern Florida.

The average U.S. residence uses about 50 million BTU per year for space heating. However, the need for space heating varies significantly in different regions of the U.S. As will be discussed in Chapter 15, a metric called “heating degree days” is used to indicate relative heating energy requirements. This metric is defined as follows:

Heating Degree Days (HDD) = Sum of (days when the average temperature is below 65°F) × (65 minus the average temperature on that day)

Table 6-1 shows data for yearly mean temperature, heating degree days, and months per year with average temperatures above 65°F in several U.S. cities.

**Table 6-1. Weather Factors Related to Heating Energy Needs**

| City          | Mean Temperature °F | HDD   | Months Above 65°F |
|---------------|---------------------|-------|-------------------|
| Hartford, CT  | 50.2                | 6,104 | 3                 |
| Laramie, WY   | 40.4                | 9,038 | 0                 |
| Denver, CO    | 50.1                | 6,128 | 3                 |
| Knoxville, TN | 59.5                | 3,531 | 5                 |
| Atlanta, GA   | 62.1                | 2,827 | 5                 |
| Houston, TX   | 68.8                | 1,525 | 7                 |
| Miami, FL     | 76.7                | 149   | 12                |

Clearly, there is much greater variation in space heating needs than in water heating needs for different locations.

An example demonstrates the calculation of collector surface requirements:

***Example 6.2***

*Consider a home in Knoxville, Tennessee, with an annual heating energy requirement of 50 million BTU. The monthly mean temperatures in Knoxville are shown in Fig-*

ure 6-5. Heating is needed for around 200 days (mid-September through May). The average heating requirement is 250,000 BTU per day.

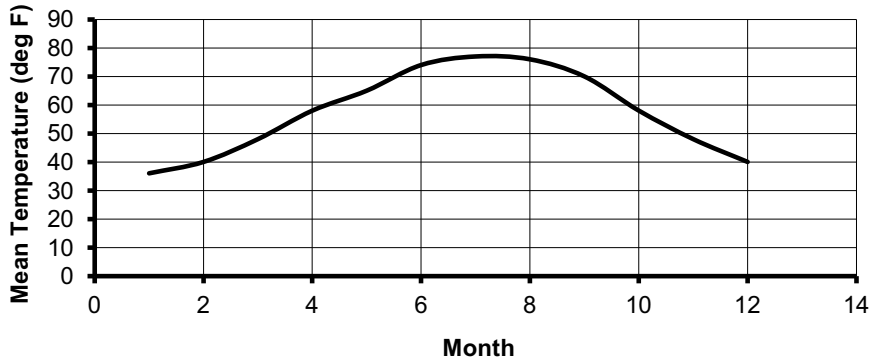


Figure 6-5. Knoxville Mean Temperatures

The pertinent solar radiation data for this example is the same as that used in Example 6.1. Figure 6-4 shows the annual variation of solar radiation seen by a fixed-axis collector oriented at 50.82 degrees and a 2-axis tracking collector in Knoxville. During the heating months, the solar energy seen by the fixed-axis collector ranges from about 1,050 to 1,550 BTU per square foot per day; the energy seen by the two-axis tracking collector ranges from about 1,200 to 2,200.

Space heating energy requirements vary significantly as daily average outside temperatures vary during the colder months. In this example, we can estimate possible ranges of acceptable collector size. For the fixed-axis collector with a collection efficiency of 50 percent, the collector surface required to supply cold-weather average energy needs is 325 to 475 square feet. For the two-axis tracking collector with a collection efficiency of 50 percent, the collector surface needed to supply cold-weather average energy needs is 225 to 415 square feet.

The storage of energy for use when sunlight is unavailable is an important issue in space heating. One option is to store heated water in an insulated water tank (see Section 15.3.4 for details about heat storage systems). A water-to-air heat exchanger would be used to heat the air in living spaces.

The required volume of water in storage depends on the energy needed and the temperature of the stored water, causing the storage volume to depend strongly on local weather and the features of the home being heated. The following example shows the calculation for a hypothetical case.

**Example 6.3**

*Consider a home in which storage capacity is needed for half of the home's energy requirement. Assume the home uses the average annual space heating energy of 50 million BTU and that heating is needed for 200 days per year. Therefore, the storage tank would have to store an average of 125,000 BTU per day. Further assume the water is stored at 120°F, and the desired heated air temperature is 80°F. Since the specific heat capacity of water is 1 BTU per pound per °F, each pound of water delivers 40 BTU when it cools by 40°F. Since the density of water is around 8 pounds per gallon, each gallon of stored water would deliver 320 BTU. The storage volume would be 125,000/320 or around 390 gallons (about 50 cubic feet). This could be accomplished with a tank having a 4-foot diameter and a 4-foot height. Since the heat needed on the coldest days would exceed the average, the storage volume would need to be somewhat larger than 50 cubic feet.*

For homes with hot tubs, the hot tub might serve for energy storage if it included proper insulation, plumbing, and controls.

**Pool Heating**

Heating pool water extends the number of days per year that a swimming pool can be used. Heating may be needed even in summer months in northern continental U.S. sites, but most American pools are in warmer regions where heating is needed only in the spring and fall.

Swimming pools generally have most of the plumbing needed for a solar heater, and the energy storage medium is the pool itself. A typical backyard pool contains about 15,000 gallons of water (about 120,000 pounds). Pool heating has two distinct operating regimes: bringing the temperature up to a comfortable level and maintaining the temperature. Bringing the temperature of cold water up to comfortable levels requires more energy input per day than maintaining water at the desired temperature. Sizing a collector for

maintaining a desired temperature may be too small for heating the water initially, and supplemental heat may be required.

Contractors have collector sizing software, and Internet sources provide sizing estimates for public use. For example, one such website<sup>3</sup> gives an estimate of solar collector surface area of 360 square feet for Knoxville. This estimate assumes unshaded pool and collector sites and the use of a pool cover at night. The rule of thumb is that collector area should be 50 to 100 percent of the pool surface area. Using the rule of thumb, a typical 15- by 30-foot pool should have a collector area of 225 to 450 square feet.

#### *Combined Heating Systems*

Of course, installed solar heating panels can provide heat for a combination of water heating, space heating, and/or pool heating if the system includes appropriate plumbing and controls. Separate heating systems might include 60 square feet for water heating, 500 square feet for space heating, and 500 square feet for pool heating. But pool heating requirements are smaller when space heating requirements are greatest. Therefore, the same collector could be used for space heating in winter and for pool heating in spring and fall. Such a system would need additional investment in valves and controls.

#### *Solar Cooling*

Vapor absorption refrigerators use heat energy to accomplish cooling (see Chapter 15). Solar energy can be used to provide the required heat.

### **6.2.3 Commercial and Industrial Solar Heating Applications**

Commercial and industrial facilities can also use solar heating systems. The principles are the same as for residential systems. Space heating is the most important application for most commercial and industrial consumers. Hotels may select solar heating systems for pool heating. Of course, energy requirements for large buildings are much greater than for homes, requiring much greater collector surface area.

## 6.3 Solar Electricity

Solar energy may be used to produce electricity in three ways. One is to use solar energy to boil water that then drives a turbine. This requires high temperatures, so producing steam from solar energy usually involves concentrating the energy by using mirrors or lenses to focus energy on a boiler. The second method for producing electricity is the use of photovoltaic devices. Photovoltaics are materials that release electrons when struck by photons. A third method, which is still speculative, would use solar heating to cause air to rise through a tall chimney. The moving air would pass through a turbine that drives an electric generator.

All of the systems for producing solar electricity function only when the sun is shining. Satisfying around-the-clock demands for electricity requires backup systems and/or energy storage (see Section 6.3.4).

### 6.3.1 Solar Heat Engines

Solar heat engines use solar energy to boil a liquid or heat a gas. Solar heat engines include solar towers, parabolic collectors, and Stirling engines. For solar towers and parabolic collectors, the target contains fluid that is caused to boil by the absorbed energy. The resulting vapor drives a turbine-generator to produce electricity. Stirling engine designs use mirrors to provide the heat source for engine operation. (Appendix D addresses Stirling engine principles.)

The solar tower design uses an array of mirrors located on the surface around a boiler mounted on a tower. Figure 6-6 shows a solar tower. The parabolic collector design uses concave mirrors that reflect solar photons onto a tube in which a fluid is heated and boiled. Vapor from an array of tubes is collected and used to drive a turbine-generator. Figure 6-7 shows a typical design.

As discussed in Chapter 2, vapor emerging from a turbine must be condensed in order to maintain a pressure difference across the turbine as needed to maintain flow. Thus, solar towers and parabolic collector systems

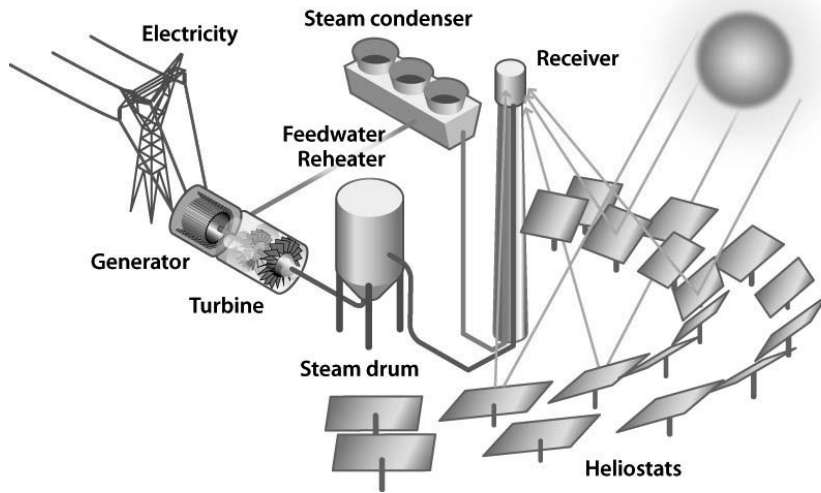


Figure 6-6. A Solar Tower (courtesy of U.S. Dept. of Energy)

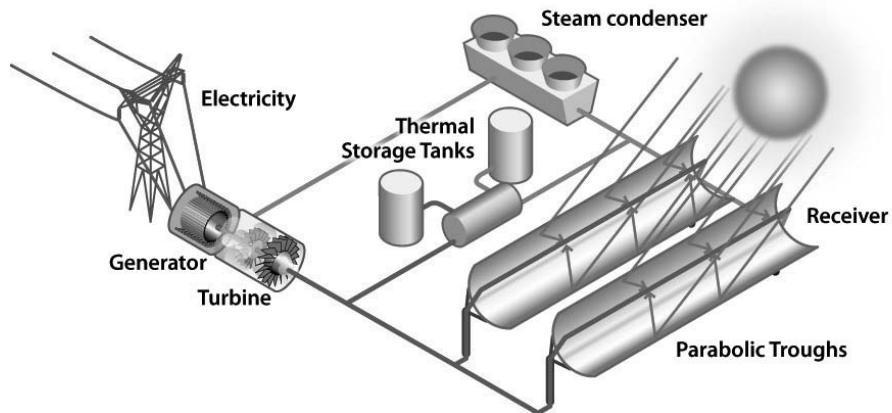


Figure 6-7. A Parabolic Solar Collector (courtesy of U.S. Dept. of Energy)

require a means to cool the turbine exhaust so as to cause condensation. Stirling engines also require cooling as described in Appendix D. In a typical power plant, the energy transferred to the surroundings is  $2\frac{1}{2}$  to 3 times the electrical energy produced.

The best (and almost universally used) heat sink is water. The heat removal capability of cooling water may be increased if some of it is allowed to evaporate, as in a cooling tower. In any case, solar heat engines require access to a large heat sink, usually water. Where water is unavailable or scarce, dry cooling (heat transfer to ambient air) may be used. However, dry cooling is significantly less efficient and more expensive than water cooling. Water unavailability may limit deployment of solar heat engines in desert areas, where land and solar insolation exist in abundance.

Since sunlight must be focused in solar heat engine applications, the light must emanate from a point. In passing through the atmosphere, some light reaches the surface without scattering, and some undergoes scattering. The unscattered light can be focused, and the scattered light cannot. About 51 percent of surface energy absorption is due to unscattered sunlight. The net efficiency of conversion of solar energy into electricity by heat engines is the product of the unscattered radiation fraction (51 percent) and the thermodynamic efficiency (30 percent) of the engine, giving an overall efficiency of about 15 percent. Typical solar heat engines would require around 330,000 acres per Quad of electricity generated.

### 6.3.2 Photovoltaics

Photovoltaic systems are in wide use for specialized applications. They are practical for low power applications, such as watches and calculators, and are widely used. They are also used in certain other, larger-scale, off-grid applications. Photovoltaics are used extensively in satellites and space stations where other energy supplies are unavailable or impractical. Modest energy needs in remote regions of underdeveloped countries can sometimes be met with photovoltaics at lower cost than building power lines. Photovoltaic systems are also being deployed in large scale central station power plants. Major growth in the construction of large solar “farms” is expected as production costs of the devices decrease due to advances in technology and to mass production.

*Photovoltaic Principles*

The basic idea in photoelectricity is transferring the energy of a solar photon to an electron in a substance, thereby creating a free electron and leaving behind a vacant space (a so-called “hole”). Devices composed of appropriate pairs of materials, called semiconductors, create a diode, a device that allows the flow of electrons in one direction and blocks flow in the opposite direction. If the two sides of the device are connected by a conductor, electrons ejected by solar photons will flow through the conductor, providing an electrical current that can be put to use. A more detailed description of photoelectricity appears in Appendix I.

Photovoltaic devices are currently capable of converting about 15 percent of incident solar energy into electrical energy. Improvements to as much as 30 percent are anticipated.

*Photovoltaic Materials and Systems*

Most photovoltaic devices are made of silicon, with small amounts of additives called *dopants*. Common dopants are phosphorous and boron. A junction is created by positioning silicon containing one dopant in contact with silicon containing the other dopant. The device is constructed as an array of thin doped silicon wafers. Figure 6-8 shows a typical device.

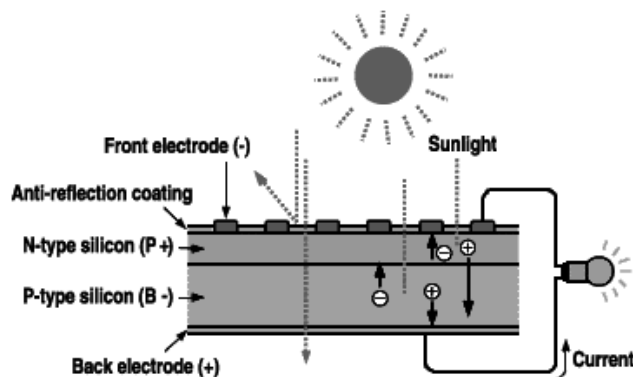


Figure 6-8. A Photovoltaic Cell  
(courtesy of National Renewable Energy Laboratory)

A newer type of photovoltaic material is the thin film type, which uses an organic polymer. These materials permit added flexibility in solar photovoltaic system design.

### *Local Electricity Production*

Photovoltaic systems may be used to provide electricity locally to residences and businesses. These systems include a photovoltaic panel and an inverter, a device that converts the direct current produced by the photovoltaic panel into the alternating current needed by most electrical devices used in homes and businesses.

In some locations, local producers can sell excess electricity to the region's utility.

Websites provide free calculation packages for use by the general public for estimating photovoltaic system performance. One such package is the "PV Watts" software provided by the National Renewable Energy Laboratory<sup>4</sup>.

### *Photovoltaic Status and Potential*

The cost of photovoltaic systems is falling, but they are still uncompetitive for large-scale electricity production systems as this book is being written. The competitiveness of solar photovoltaic electricity depends on three main factors:

- The initial cost of the photovoltaic system
- The interest rate on the capital expenditure (almost all of the cost of photovoltaic electricity is for debt service)
- The cost of electricity from competing conventional producers

As photovoltaic systems reach cost parity with other systems, it is expected that the number of local electricity production systems in homes and businesses and large photovoltaic farms will increase significantly.

It is noteworthy that photovoltaic systems do not require cooling, and, therefore, desert areas can potentially host large installations.

For photovoltaics that operate at 15 percent efficiency, about 330,000 acres of land area would be required per Quad of electricity (about the same as the land required for solar heat engines). If the anticipated improvement to 30 percent occurs, the land requirement drops to 165,000 acres. For comparison, the state of Arizona covers 73 million acres.

### 6.3.3 Solar Chimneys

A third type of system for producing solar electricity has been proposed. In this approach, a large area covered by plastic sheeting surrounds a tall, hollow tower. The air under the sheeting experiences solar heating. The heated air rises through the tower. Turbines in the air flow path at the base of the tower drive electrical generators. This approach is very simple in principle, but large commercial systems have not appeared due to technical immaturity and the need for the large (and expensive) systems that are believed necessary for achieving competitiveness.

### 6.3.4 Dealing with Intermittency

Since operating costs for solar electricity production are negligible, there is an incentive to use all that can be produced in solar power plants. This means other power plants must increase or decrease production as solar power production decreases or increases. Solar power production is naturally intermittent. It varies with the time of day and with the extent of cloud cover. Using all of the solar electricity as it is produced is suitable as long as solar power production is small enough to place acceptable power production demands on other plants that are assigned load-following duty. These load-following plants must change production continuously to compensate for changes in solar electricity production. When solar power generation capacity grows, it places increasing demands for frequent changes in generation on the load-following plants, causing wear and tear and sub-optimal operation. At some point, the demands become excessive. When this happens, it becomes desirable to store some or all of the energy from solar plants and release the stored energy as needed. Batteries and capacitors are capable of storing energy.

Solar heat engines can reduce problems due to intermittency by storing heat energy. Excess energy from the collector is used to heat a medium such as molten salt. The hot medium subsequently transfers its energy to the working fluid, which then is used to produce electricity when sunlight is unavailable. Since there is no transformation of one form of energy into another in storing or recapturing energy (both are heat energy), this method of storing energy is quite efficient.

Photovoltaic systems produce electricity directly, and electricity cannot be stored except in capacitors. Other possible storage methods such as pumped storage (see Section 9.5), battery storage, or hydrogen production involve transforming energy from one form to another in storage operations and in recovery operations. Since there is always energy loss in these transformations, the recoverable energy is less than the electricity initially produced photovoltaically.

Regardless of the storage method used, there is a cost penalty because of the added equipment and the lost energy.

Small photovoltaic systems in homes or businesses can deal with intermittency by sharing production with grid sources. During the day, photovoltaic production occurs, and the demands for grid electricity are greatest. If the local photovoltaic system produces more electricity than the local requirement during the day, excess electricity can be fed into the grid. At night, when the local producer is idle, the grid can feed electricity into the home or business. In this way, the home or business sells electricity when possible and buys electricity when needed. This benefits the home or business and reduces peak production generation requirements for the utility.

## 6.4 Looking Ahead

Solar energy has the potential to become a major part of America's energy supply in the future. Current research is increasing efficiency and reducing unit costs. But much remains to be done. Manufacturing and installing solar systems that are competitive with traditional energy sources is a major

challenge. Even assuming that costs become competitive soon, it will take many years to manufacture and install enough systems to contribute significantly. Associated infrastructure changes must also be built to accommodate intermittency and the remoteness of desirable sites for energy farms.

Solar energy proponents are appropriately enthusiastic about its potential for producing ample, cheap, clean energy. But building a large-scale solar energy system will require time, money, and commitment.

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2. Energy Matters “My Solar Estimator” at <http://estimator.solar-estimate.org>.
3. The Solar Direct Company “VORTEX Solar Pool Heating Automated System Sizing” at [http://www.solardirect.com/pool\\_heaters/solar\\_pool\\_heating/calculator.htm](http://www.solardirect.com/pool_heaters/solar_pool_heating/calculator.htm).
4. National Renewable Energy Laboratory “PV Watts” calculator at <http://www.nrel.gov/rredc/pvwatts>.

## Exercises

- 6-1. Find the average solar energy absorption rate in January for a horizontal surface in your location. Assume the energy required to heat water is 50,000 BTU per day. How many square feet of horizontal surface would be needed in a solar water heater that operates at 50 percent efficiency? What would happen to the surface area requirement if the collector were tilted?
- 6-2. How much energy (BTUs and kilowatt hours) would be captured by a collector in Knoxville with 40 percent efficiency in January by a two-axis tracking collector with two hundred square feet of surface?

- 6-3. Estimate the ratio of heating energy requirements in Laramie to the required heating energy requirements in Atlanta.
- 6-4. Compare the January solar energy available in Laramie and Atlanta.
- 6-5. Discuss the implication of the results from Exercises 6.3 and 6.4.
- 6-6. A homeowner decides to insulate his hot tub and use it for storing solar energy collected during daylight hours in winter. The tub holds 150 cubic feet of water. How much energy (BTUs and kilowatt hours) is stored per day if the daytime solar heat raises the water temperature to 100°F (38°C) and the water cools to 80°F (27°C) at night when used to warm the home?
- 6-7. Tilting solar collectors reduces the area of the collector, relative to a horizontal collector, that is needed to absorb equal amounts of solar energy, but does not change the horizontal footprint of the collector system. Explain.
- 6-8. Estimate the cost of heating a 15,000 gallon swimming pool from 60°F to 80°F (16°C to 27°C) with electric heaters (assuming zero heat loss during heating) if electricity costs 11 cents per kilowatt-hour.

