Solar Energy

13

Give me the splendid silent sun, with all his beams full-dazzling!
—Walt Whitman, *Drum-Taps*

13.1 General Characteristics of Solar Energy

Throughout human history, solar energy has been utilized for domestic use in heating and cooking. The Anasazi Indian tribes of the American Southwest were perhaps the first in North America to employ passive solar energy in their dwellings. The Greeks and Romans documented their use of solar power in Europe over two millennia ago. In the early eighteenth century, specific solar technologies were introduced to concentrate the sun's energy and put it to use in high-temperature processes. The development of a 1,700°C solar furnace by Lavoisier in the mid-1700s is an excellent early example of human progress in harnessing solar energy. In general, its ubiquitous nature and ability to be used effectively over a range of scales make solar the popular choice among renewable energy enthusiasts today.

As discussed in chapter 2, the sun's energy incident on the earth is the intrinsic source for many forms of renewable energy (including wind, ocean thermal, and bioenergy) and, over a longer time scale, for all of fossil energy. Technologies for capturing solar energy have been actively pursued for over a century, with much engineering know-how and analysis developed during the last 50 years. As a result, the documentation available for solar energy is extensive. Those interested in more depth should examine the resources listed at the end of the chapter.

In this chapter, after discussing the characteristics of the solar energy resource, we will review capture and utilization technologies. Our treatment is limited to brief summaries of the main technical, economic, and policy issues for three modes of solar energy use:

- in the form of thermal energy collected passively or actively for heat that is used in space-conditioning buildings or other direct applications;
- in the form of thermal energy that is collected in solar concentrators and converted to electricity;
- the direct conversion of solar energy to electricity using photovoltaic devices.

The means of converting solar energy to useful heat or to electricity depends on the local quality of the solar resource and on the end use of the energy—whether for residential, commercial, or utility use. Solar thermal installations are mostly residential but are increasingly seeing commercial use. For example, in 2008 a solar thermal water-heating system was installed at Boston's Fenway Park, providing about one-third of the ballpark's hot water. Local photovoltaic (PV) electricity generation below about 10 kW_e is used for residential buildings; PV installations up to about 100kW_e appear on both residential and commercial properties. Commercial PV installations up to 1 MW_e and a few utility installations up to 10 MW_e exist. Above the 10 MW_e scale (and even exceeding 100 MW_e), concentrating solar power (CSP) installations are being installed by utilities for power generation. These larger installations are sited in high-quality solar flux areas and are optimized with various types of tracking, often including tracking devices. At the larger scales, dispatchability becomes an issue, and storage or an auxiliary dispatchable power system is incorporated as part of the design.

In 2007, there were about 7 GW_e of smaller PV systems (under 100 kW_e) installed worldwide; about 0.7 GW_e of larger PV installations (100 kW_e to 10 MW_e); and about 0.5 GW_e of mostly CSP systems for the larger utility-scale installations above 10 MW_e. Several European countries and Japan, which have higher energy prices than the US, have enacted policies such as feed-in tariffs to encourage the installation of solar and other renewable technologies. As of 2008, Germany had 5,308 MW_e of installed solar electric capacity, Spain had 2,973 MW_e, Japan had 2,173 MW_e, and the US had 1,547 MW_e.

A more recent source of information on solar energy is a special report on renewable energy that devotes a detailed chapter to topics similar to those discussed in this chapter (IPCC, 2011).

13.2 Resource Assessment

Almost everyone qualitatively appreciates the variability of the sun's intensity during the day as the sun passes overhead and as its radiation encounters clouds in its path to the earth's surface. Seasonal variations are then superimposed on top of these diurnal changes. Fortunately, the daily and seasonal movements of the sun are both predictable and known in precise mathematical form. Changes in weather are less regular but can be averaged for estimating the solar potential in different regions. The intermittent and variable characteristic of solar energy must be reckoned with to make effective use of it as a source of thermal or electrical energy. Passive or active storage in some form is almost always coupled to a solar energy system.

The intrinsic source of the sun's energy is a direct result of the thermonuclear fusion of hydrogen nuclei to form helium, which occurs at the phenomenally high rate of about 4×10^9 kg of mass conversion per second (Hinrichs, 1996). The solar fusion reaction results in a temperature of about 6,000°C at the sun's surface that, in turn, induces a large solar radiative flux that travels 93 million miles (150 million kilometers) to the earth.

The distribution of the solar energy flux that intercepts the earth is a strong function of the wavelength of the incident light (as shown in the solar spectrum of figure 13.1). Because of variations in the absorption and reflection characteristics of different molecules contained in the earth's atmosphere, the distribution changes from the top of the atmosphere to the earth's surface. For example, most of the

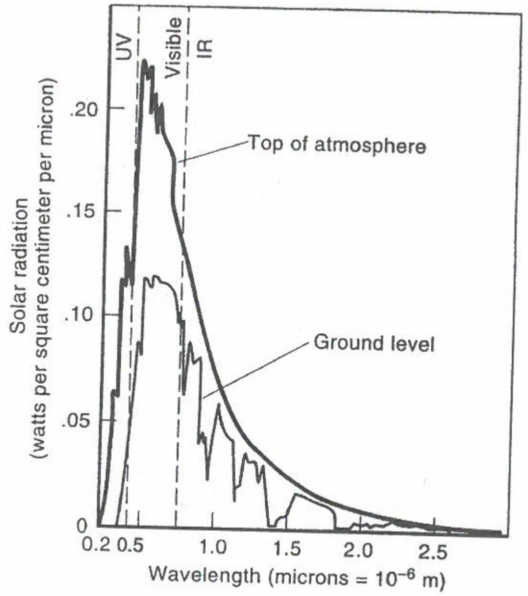


Figure 13.1
The solar spectrum, distribution of incident energy as a function of wavelength at ground level and at the top of the earth's atmosphere. Adapted from Hinrichs (1996) and Kreith and Kreider (1978).

short wavelength ($\lambda < 0.4$ micron) ultraviolet radiation is absorbed by oxygen (O_2), ozone (O_3), and nitrogen (N_2) in the upper atmosphere, while H_2O and CO_2 capture a good portion of the longer wavelength radiation ($\lambda > 0.6$ micron) in the visible and infrared region.

The incident solar energy flux on the earth's surface is large. In general terms, the energy flux or total insolation that strikes the top of the earth's atmosphere is referred to as the *solar constant* and has a value of 1,354 W/m^2 (or equivalently 429 Btu/ft^{2}hr, 1.94 Langleys/min, or 4,870 kJ/m^{2}hr). Depending on the time of day and the month of the year, as well as the local weather and latitude of a particular location on the earth's surface, the amount of insolation that actually reaches the surface will vary from essentially 0 to about 1,050 W/m^2. On average, about half of the energy incident on the earth's upper atmosphere makes it to the surface, with the rest scattered, reflected, or absorbed and reradiated into space. About 21% of the solar flux reaches the surface as direct radiation and about 29% as scattered or diffuse radiation.

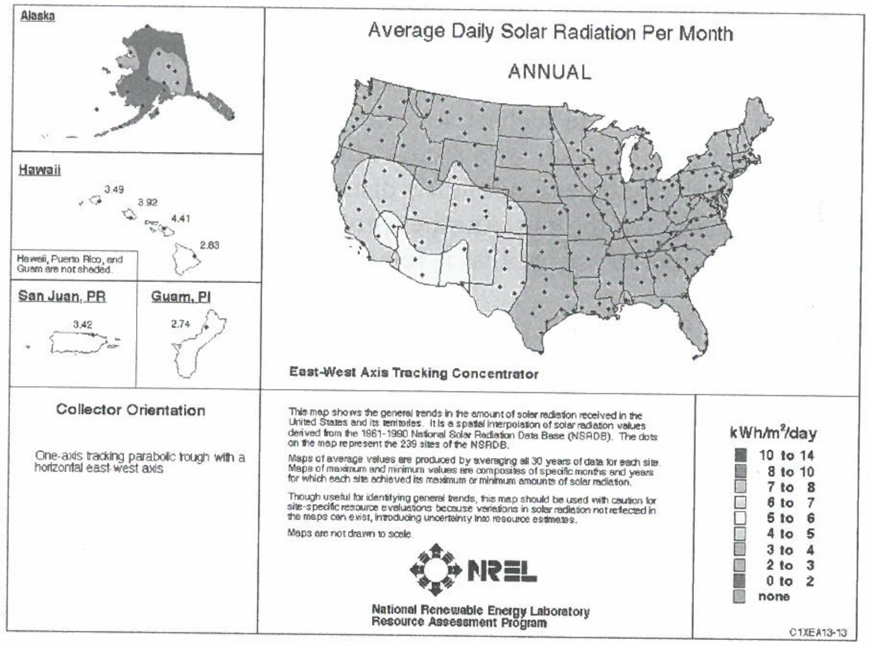
Even with these losses, the amount of solar energy that reaches us is significant. For example, over 40,000 EJ of solar energy are incident on the US each year, which

is about 400 times the total US primary energy consumed during all of 2009. Given this, why haven't we used solar energy more effectively to displace our demand for fossil fuels? Part of the problem has to do with the intermittent and seasonal variability of solar radiation. The highest solar fluxes are available during the period around noon, and they can vary by a factor of two or more from month to month depending on local cloudiness, humidity, distance to the equator, and seasonal changes in the position of the sun. Another problem has to do with the low density of solar energy relative to energy that is released chemically due to combustion of fossil fuels.

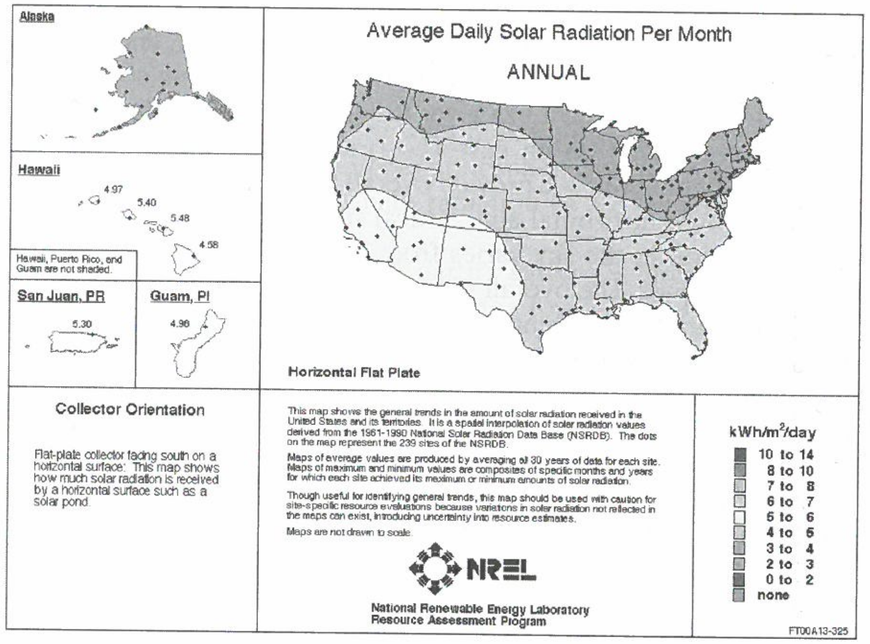
We can grossly characterize the solar flux or insolation as having two forms: direct and diffuse light. The direct or unscattered portion can be focused or concentrated using mirrors or lenses, while the diffuse portion, which results from scattering by clouds and the atmosphere itself, cannot be focused. Scattering in the atmosphere can also be locally influenced by the presence of surface-emitted aerosols and particulates, especially in or near large urban areas. The summation of direct (adjusted by the cosine of its incident angle) plus diffuse radiation represents the total flux that hits the surface. Plate 7 shows the US solar photovoltaic resource in average annual daily insolation (kWh/m^2-day) for a tilt latitude collector. For maximum collection, solar panels in the Northern Hemisphere should always be pointed toward the south (and vice versa), but their tilt angle varies both by latitude and by season. The latitude tilt angle is the basic adjustment, and ±15° is a typical seasonal adjustment. Plate 7 also shows the US concentrating solar resource (discussed in section 13.4). Figure 13.2a gives the US annual average of direct (unscattered) insolation incident on an east-west-oriented concentrator that tracks the sun's path, while figures 13.2b–c provide overall US annual averages of total insolation incident on both horizontal and vertical surfaces.

The sun's position in the sky varies from hour to hour, as well as from day to day, as the seasons pass. The overall motion of the sun has been characterized and correlated with various mathematical formulae and is available in graphical and tabular form (Michalsky, 1988). The orientation of the collector surface relative to the sun's pointing angle is a key element in determining the collector's capture efficiency. To optimize the amount of energy recovered, the collector can be designed to track the sun's position or it can be oriented in a fixed position that is purposely selected to maximize recovery during certain times of the day or year. Systems that concentrate the solar flux by focusing energy on a fixed receiver usually track the sun's position continuously, while flat-plate solar heating and photovoltaic (PV) systems usually have fixed orientations. (Details are provided in sections 13.3 through 13.5, where specific technologies are discussed.)

In practical terms, the capture efficiency (η_{solar}) of any solar collector can be represented by:

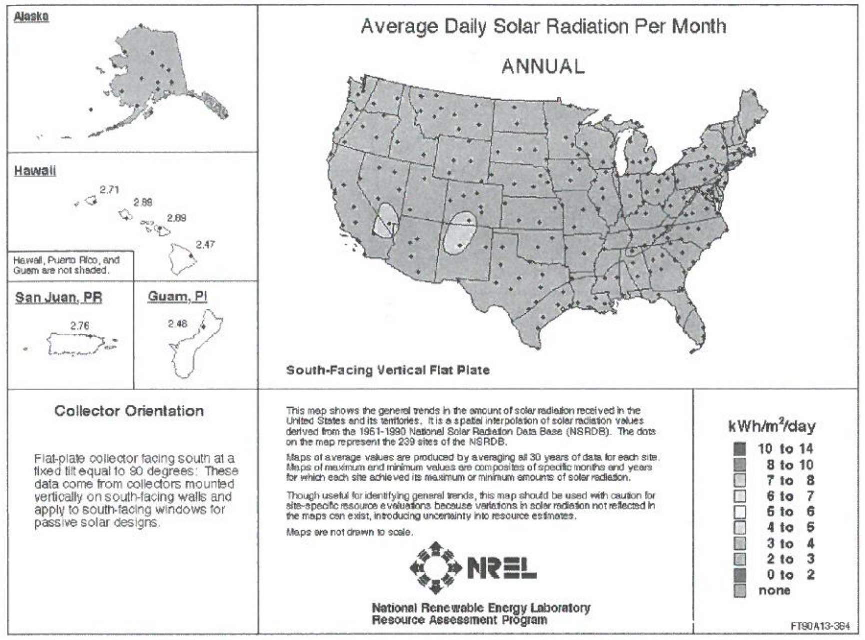


(a)



(b)

Figure 13.2
The solar resource for the US: (a) average daily direct insolation for an east-west tracking concentrator, (b) average daily total insolation flux for a horizontal flat plate, and (c) average daily total insolation for a south-facing vertical flat plate. Source: Renne et al. (2002).



(c)

Figure 13.2
(continued)

$$\eta_{solar} \equiv \frac{\text{useful energy recovered}}{\text{total insolation incident on the collector}} \times 100\%. \tag{13.1}$$

Recovered energy can be in the form of thermal energy (heat) or electrical energy (current × voltage). In recovery applications for thermal energy, efficiencies can be high, ranging from 30–60% or more. In photovoltaic systems, efficiencies are considerably lower, with 8–15% being typical.

An operating variable that influences the capture efficiency of any solar collector is the pointing error, Ψ, which can be represented using the following nomenclature:

$$\Psi \equiv \text{pointing error} = \xi - \beta \text{ in degrees} \tag{13.2}$$

and

$$\alpha \equiv \text{collector tilt relative to the latitude} = \beta - \varphi$$

where

β = tilt angle of the collector in degrees from the horizontal
φ = latitude in degrees
ξ = pointing angle of the sun.

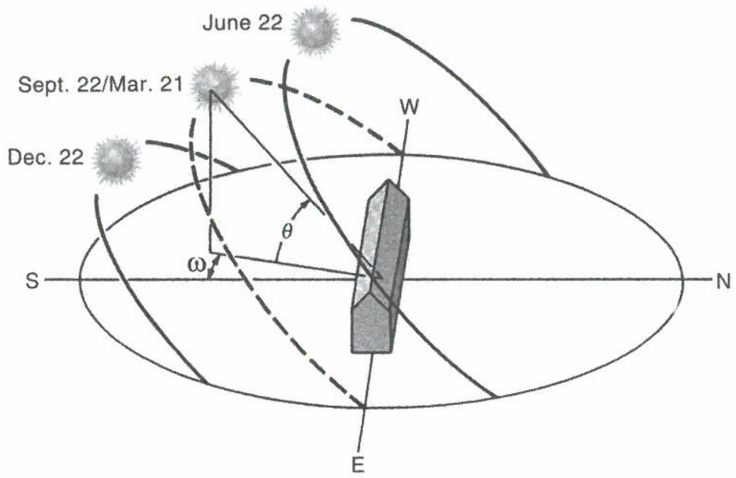


Figure 13.3
Schematic showing the definition of the hour angle (ω) and the solar altitude angle (θ) of the sun relative to an east-west-oriented structure. Adapted from Hinrichs (1996) and Kreith and Kreider (1978).

Also important are two other orientation angles:

θ = altitude angle in degrees

ω = azimuth in degrees.

The altitude angle θ and azimuth ω are defined as the angle of the sun above the horizon and the angle from true south, respectively, and are illustrated in figure 13.3. Figure 13.4 illustrates the geometric relationship among these angles. The hourly variations of the sun's position are usually represented by the azimuth or hour angle, ω, that varies about 15° per hour and ranges from 0 to a maximum value that changes depending on the time of the year. ω is 0 at solar noon when the sun reaches its highest position in the sky for a specific location, and reaches a maximum value when the sun sets below the horizon. The maximum value is <90° in fall and winter months and >90° during spring and summer months. Seasonal variations are usually given as a function of the declination angle, δ, which provides a quantitative measure of the tilted earth's position relative to the sun as the earth moves around the sun annually (see figure 13.5). δ is 0 at the autumnal and vernal equinoxes, September 21 and March 21, respectively, and in northern latitudes, it is +23.5° at the summer solstice on June 21, and −23.5° at the winter solstice on December 21.

For collectors facing the equator, $0° < \beta < 90°$; for collectors facing away from the equator, $90° < \beta < 180°$. Overall, a transcendental equation must be solved to

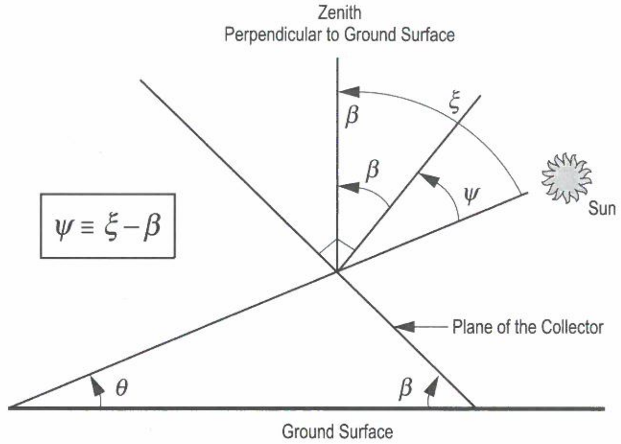


Figure 13.4
Geometric relationship among various angles characterizing the relative position of the sun to the solar collector surface.

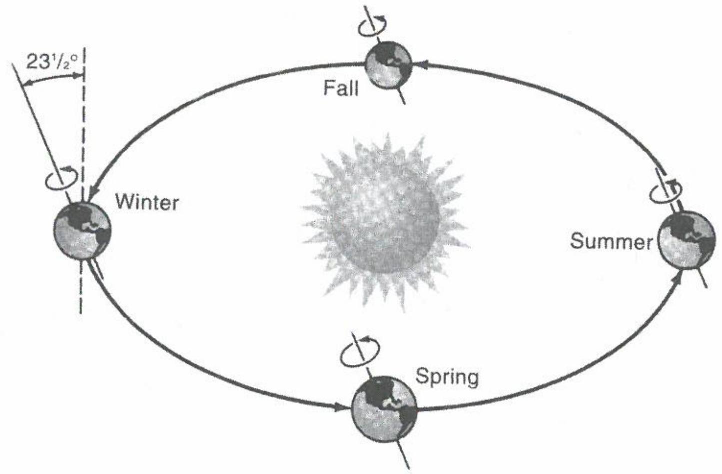


Figure 13.5
The yearly orbit of the earth around the sun. Adapted from Hinrichs (1996). © 1996 Brooks/Cole, a part of Cengage Learning. Reproduced by permission.

determine how the pointing angle, ξ, varies as a function of both hourly and seasonal positional changes. In general terms, the relationship is given by

$$\tan\frac{[90-\varphi+\zeta]}{2} = f(\delta,\omega) = \text{complex trigometric function} . \tag{13.3}$$

Figures 13.6–13.8 illustrate these effects by showing how the sun's altitude angle varies as a function of the azimuth angle for three different northern latitudes (28°, 36°, and 44° north).

To underscore the importance of orientation, we will give three examples of how collectors are normally placed. For sites where the domestic heating and hot-water loads are high during the winter months, solar thermal flat-plate panels would be oriented facing south with a tilt angle greater than the latitude, typically at $\beta = \varphi + 15°$, to capture more of the sun's energy when it is lower in the sky nearer the

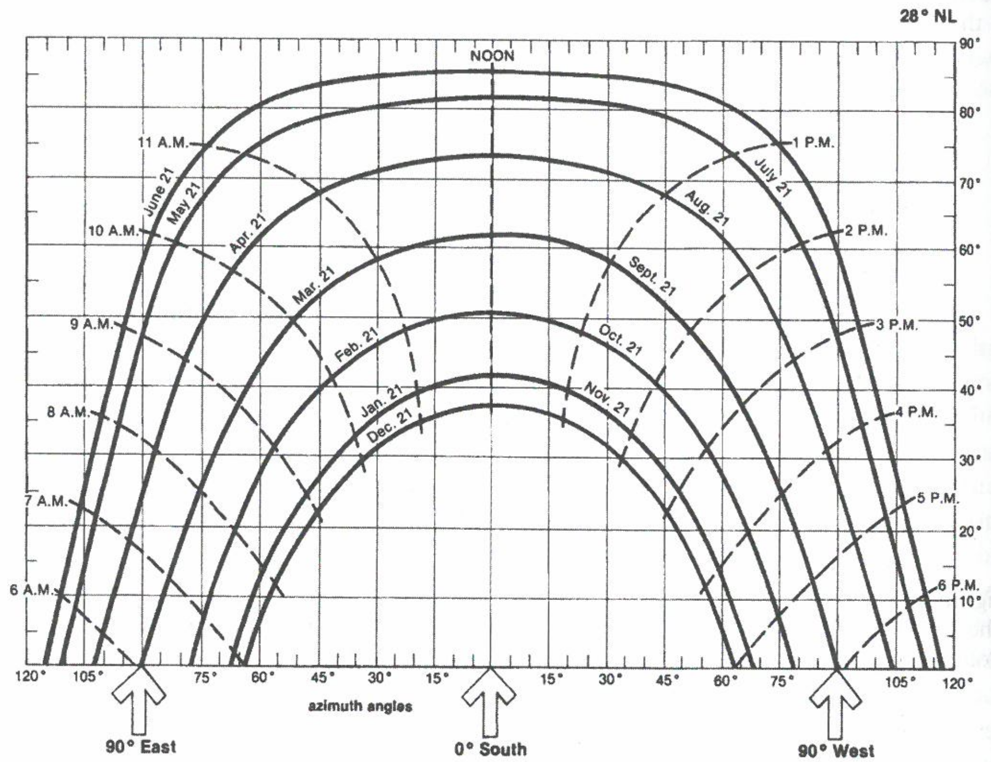


Figure 13.6
The variation of the sun's altitude angle as a function of azimuth or hour angle for latitude 28° north of the equator. Adapted from Keisling (1983) and Kreith and Kreider (1978).

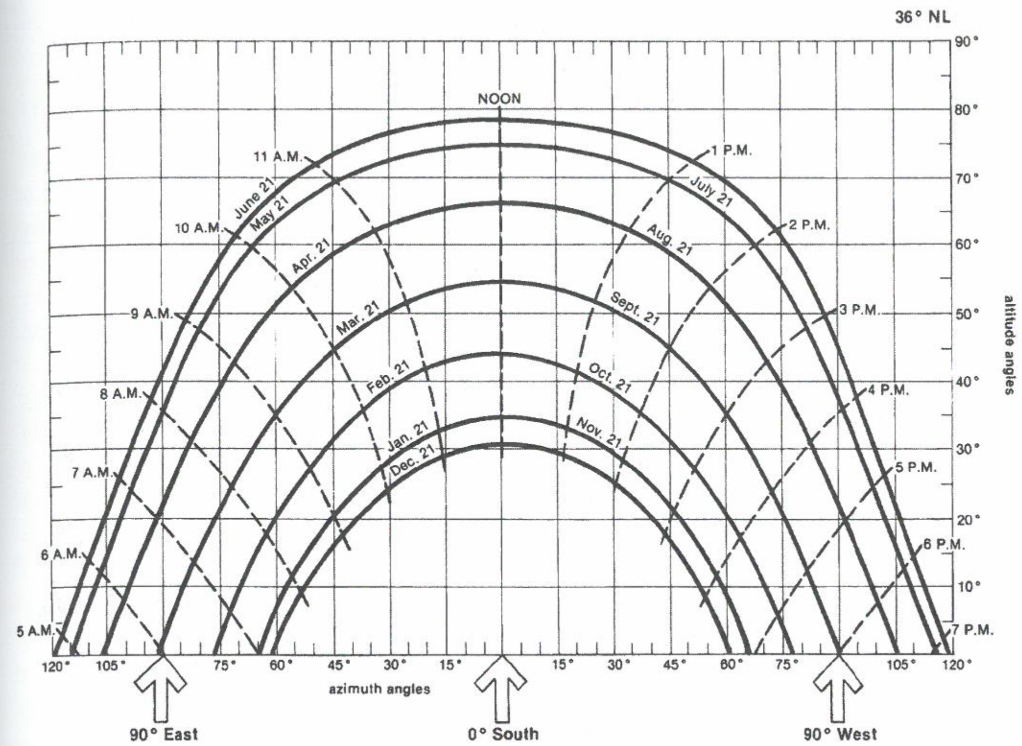


Figure 13.7
The variation of the sun's altitude angle as a function of azimuth or hour angle for latitude 36° north of the equator. Adapted from Keisling (1983) and Kreith and Kreider (1978).

horizon. For year-round solar heating, flat-plate collectors would commonly be oriented to face south at a tilt angle equal to the latitude ($\alpha = 0$ and $\beta = \varphi$). For sites where the air conditioning and electric loads are larger during the summer, flat PV panels would be placed facing south, but at a tilt angle less than the latitude, typically at $\beta = \varphi - 15°$ or $\alpha = -15°$ or so, given the sun's higher position in the sky. These choices are not optimal in a mathematical sense, as continuous, two-axis tracking would be needed to maximize efficiency, yet they do represent reasonable tradeoffs to improve performance while maintaining the simplicity of using a fixed-orientation collector.

In addition to latitude, regional location is also important in determining the quality of the solar resource. Table 13.1 gives some representative monthly values for total, direct, and diffuse insolation. For example, two sites—Miami, Florida, and Los Angeles, California—have similar latitudes of 25°N but have far different levels of insolation.

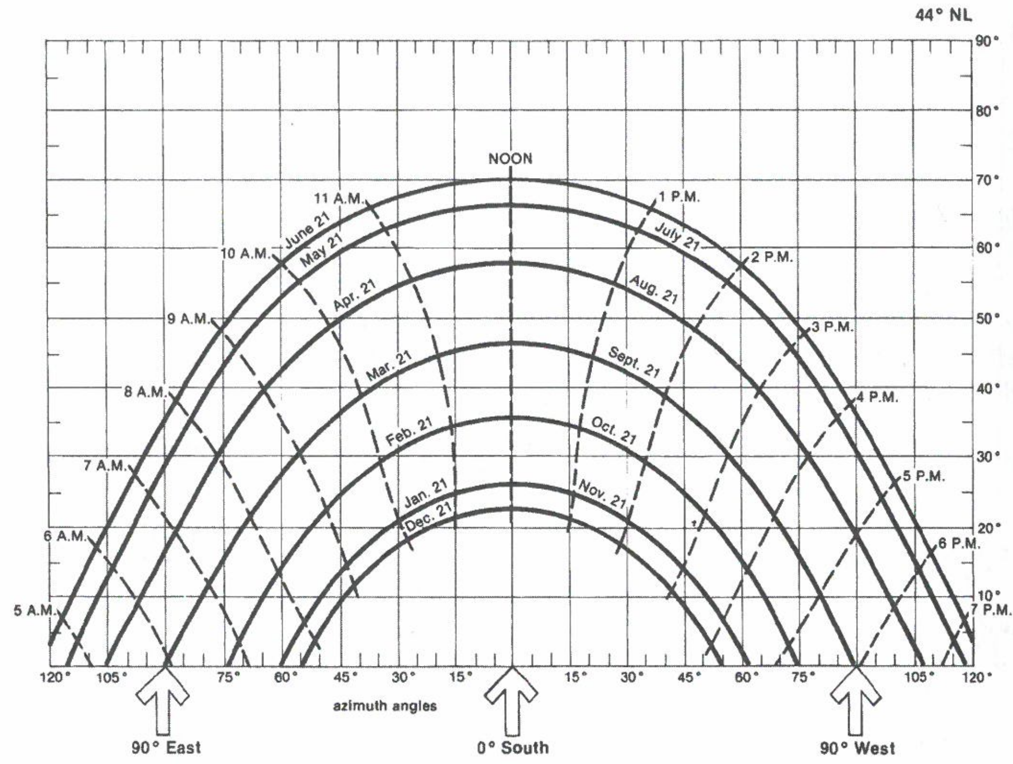


Figure 13.8
The variation of the sun's altitude angle as a function of azimuth or hour angle for latitude 44° north of the equator. Adapted from Keisling (1983) and Kreith and Kreider (1978).

13.3 Passive and Active Solar Thermal Energy for Buildings

13.3.1 Motivation and general issues

About one-third of the energy we consume is used to heat, cool, and humidify or dehumidify the buildings we live and work in (see chapter 20). In developed countries and megacities worldwide, people typically spend over 80% of their time inside such buildings. As such, indoor air quality can be a significant health issue that is strongly linked to energy use. The amount and type of energy required to condition buildings is dependent on the climate conditions of the region where they are located.

The use of solar thermal energy in buildings usually involves one or more of the following approaches:

Table 13.1
Total (Direct and Diffuse) Insolation on Horizontal Surface in Btu/ft^2 per day (Langleys per day)

Location	Latitude	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Albuquerque, NM	35°	1151 (312)	1454 (394)	1925 (522)	2344 (635)	2560 (694)	2757 (747)	2561 (694)	2387 (647)	2120 (575)	1640 (444)	1274 (345)	1052 (285)
Atlanta, GA	33.5°	848 (230)	1080 (293)	1427 (387)	1807 (490)	2018 (547)	2103 (570)	2003 (543)	1898 (514)	1519 (412)	1291 (350)	998 (270)	752 (204)
Bismarck, ND	47°	587 (159)	934 (253)	1328 (360)	1668 (452)	2056 (557)	2174 (589)	2305 (625)	1929 (523)	1441 (391)	1018 (276)	600 (163)	464 (126)
Boston, MA	42°	505 (137)	738 (200)	1067 (289)	1355 (367)	1769 (479)	1864 (505)	1860 (504)	1570 (425)	1268 (344)	897 (243)	636 (172)	443 (120)
Boulder, CO	39°	750 (203)	1030 (279)	1390 (377)	1750 (630)	1960 (531)	2160 (585)	2120 (575)	1890 (512)	1580 (428)	1200 (325)	830 (225)	670 (182)
Ithaca, NY	42°	434 (118)	755 (205)	1074 (291)	1322 (358)	1779 (482)	2025 (549)	2031 (550)	1736 (470)	1320 (358)	918 (249)	466 (126)	370 (100)
Los Angeles, CA	25°	890 (241)	1150 (312)	1520 (412)	1920 (520)	2030 (550)	2090 (566)	2260 (612)	2070 (561)	1670 (453)	1320 (358)	1000 (271)	820 (222)
Miami, FL	25°	1292 (350)	1554 (421)	1828 (495)	2026 (549)	2068 (560)	1991 (540)	1992 (540)	1890 (512)	1646 (446)	1436 (389)	1321 (358)	1183 (321)
Washington, DC	39°	632 (171)	901 (244)	1255 (340)	1600 (434)	1846 (499)	2080 (564)	1929 (523)	1712 (464)	1446 (392)	1083 (293)	763 (207)	592 (161)

Source: Renne et al. (2002)
1 Langley = 3.69 Btu/ft^2 = 41.86 kJ/m^2 = 1 cal/m^2

1. passive thermal gain and reuse,
2. active capture of solar heat using solar collectors,
3. direct or indirect daylighting.

The first two require some type of thermal energy storage and a means for distributing the thermal energy. All three require incorporation in the design of a building. In most instances, both direct and diffuse solar radiation is collected on a flat surface exposed to the sun's radiation where the absorber area is equal to the collector area. In some cases, where the collector area is larger than the absorber area, a concentrating approach may be used to achieve higher storage temperatures.

In addition to capturing a portion of the solar spectrum for use, proper building design should strive for high performance by maximizing energy efficiency. This approach usually leads to increased building insulation (higher thermal resistance or "R" values, reduced air infiltration and leakage) in the walls, floor, and roof, and better window placement and materials. There are tradeoffs, of course, given the costs associated with reducing heat losses or heat gains, that must be balanced against the benefits of having lower energy demand. For example, indoor air quality can be compromised in a well-insulated building with low air-infiltration rates. In these cases, properly designed systems for air exchange with energy recovery are needed. Nonetheless, it is safe to assume that a building that has a passive or active solar thermal system is also designed for high energy efficiency. (Chapter 20 documents these sustainability aspects in more detail.)

13.3.2 Passive systems

The basic approach of passive systems is to utilize the building's structure to capture solar heat and transmit light, where appropriate, to reduce artificial lighting needs. Certain building materials, such as stone, cement or concrete, and adobe clay, have natural characteristics that are ideally suited to capture and store heat. In a typical daily cycle, heat is collected and stored during the day and transferred by natural convection of air or water to condition the inside of the building over a period of time that extends into the evening.

Building location and orientation relative to the sun's movement is important in determining exactly what type of passive design will work best. In addition, different building types pose different challenges. For instance, windowless or closed commercial office buildings that are loaded with people, lighting, fixtures, and computer workstations represent a discrete set of small heat sources that introduce a substantial cooling load even in the winter months. Residential units with a lower density of people, greater opportunity for natural ventilation, and daylighting are better suited for classical passive designs.

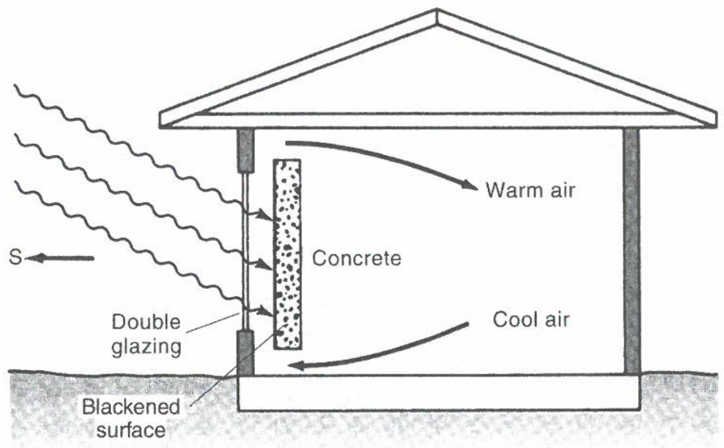


Figure 13.9
Schematic of a Trombe wall for passive capture of solar energy. Adapted from Hinrichs (1996). © 1996 Brooks/Cole, a part of Cengage Learning. Reproduced by permission.

Adobe and Trombe walls (as shown in figure 13.9) represent popular options for certain locations. These options take advantage of the relatively high heat capacity and low thermal diffusivity of the solid stone or masonry material to store and transfer heat to the inside of the building. A combined mechanism of transient heat conduction through the wall material is coupled with natural convection of air in the building. Normally, the wall is placed on the south-facing side of the building, and it may be coated with a black or darkened surface to increase its solar absorptivity and covered with glass on the side facing outward, with an air space between glass and wall. To reduce heat losses, the back and side surfaces may be insulated. A roof overhang is often used to limit the amount of solar gain during the hotter summer months. Alternatively, placing a set of windows or a greenhouse on the building's south side to heat a stone, brick, or masonry floor of the room will accomplish a similar passive effect.

More recently, variations on the Trombe wall concept have made the walls more flexible and adaptable to a wider variety of building applications. The "transpiring wall" is one such idea. Introduced a number of years ago by engineering scientists at the National Renewable Energy Laboratory (NREL) (see figure 13.10), transpiring walls have been effective for both passive heating and cooling applications.

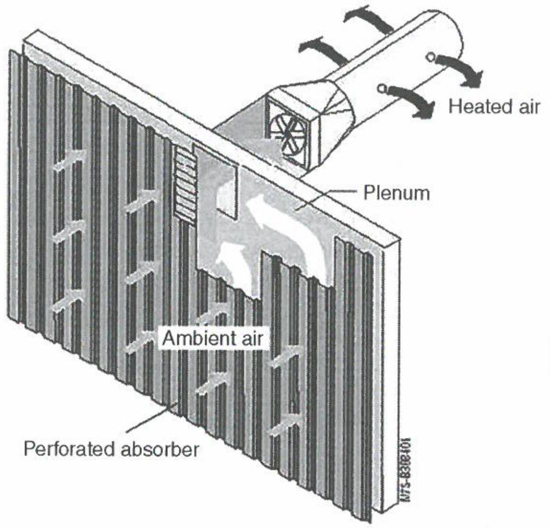


Figure 13.10
The NREL transpired passive solar collector, configured as a vertical-wall structure element. Source: Renne et al. (2002).

13.3.3 Active systems

Active solar thermal systems are usually applied in residences and commercial buildings for providing hot water, heating, and air conditioning. What makes them different from passive systems is that they employ collectors that capture solar energy and rapidly transfer thermal energy to a circulating working fluid, which can be used immediately in the dwelling or stored for later use. Control systems are almost always employed to turn circulation pumps on and off and to divert fluid to storage vessels when collector temperatures reach specified levels.

Active systems have been in operation for over 80 years, mostly employed in homes for hot water or space heating. A typical design for supplying domestic hot-water heating in a residence is shown in figure 13.11. Here we see a flat-plate collector that consists of a selectively coated metal plate with attached channels, as illustrated in figure 13.12. A circulating fluid is heated as it is pumped through the channels on the collector and then passed to a coil contained inside a hot-water storage tank, where it transfers heat to the water in the tank. In the example shown in figure 13.11, an antifreeze solution (typically a propylene glycol–water mixture) is used as the working fluid to avoid freezing and subsequent damage to the collector system during the winter. Alternatively, water could be employed with a gravity drain back loop to eliminate concerns about freezing.

Today, most flat-plate collectors are modules that can be mounted on a roof or built into the roof structure. Each one contains a metal receiver that has been

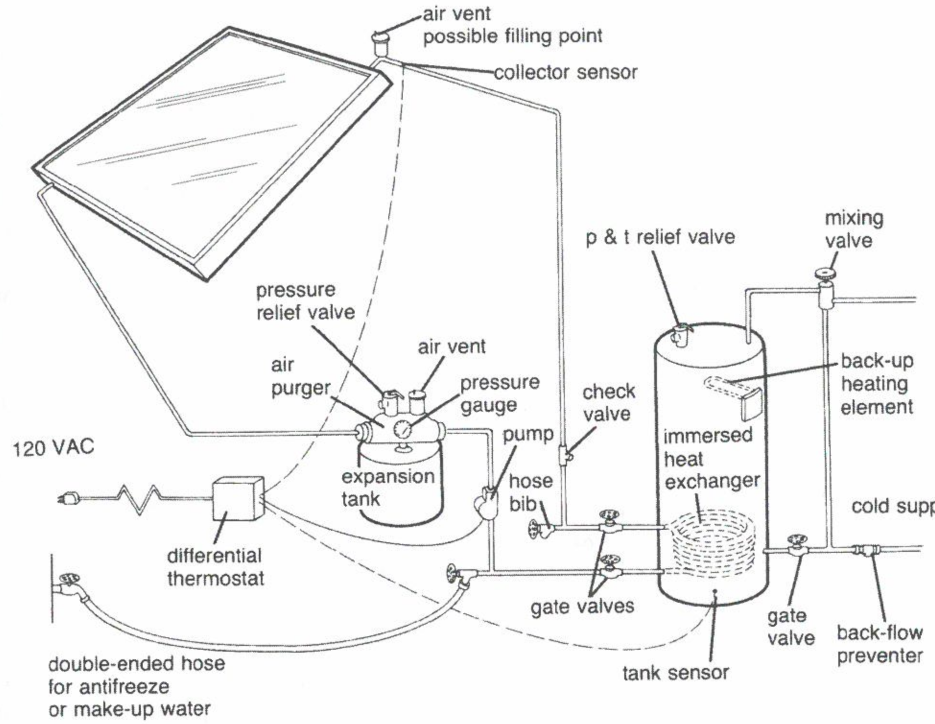


Figure 13.11
Typical active solar hot-water system. Adapted from Keisling (1983).

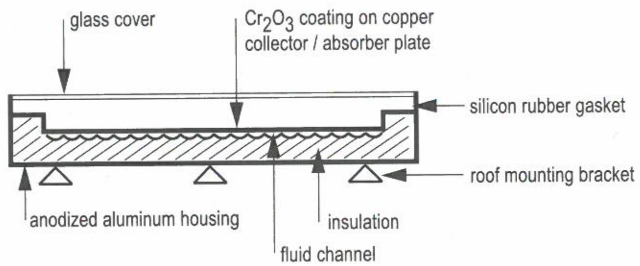


Figure 13.12
Schematic of a flat-plate solar collector for application in a domestic hot-water heating system.

coated with special materials to produce a selective surface that has a high absorptivity for solar energy ($\alpha^* > 0.95$) in the visible and ultraviolet region at shorter wavelengths (< 2 μm) and a low emissivity in the longer wavelength, thermal infrared region ($\varepsilon^* < 0.15$). This selectivity lowers the radiative heat loss from the collector surface. Although many materials have been used as selective surfaces, a favored material is a black chrome oxide, Cr_2O_3. To reduce heat losses from the collector, insulation surrounds the sides and back, and one or two transparent glass or plastic plates are positioned on the topside of the collector with an air gap of 1 cm or more. The transparent cover material is chosen based on a number of factors, including its ability to transmit solar energy with small losses, its durability despite the weather (wind, rain, and ice), and its cost. Tempered glass is often selected for solar hot-water heaters due to its low cost and durability, even though it is opaque to radiation in the infrared region. An electronic control unit regulates the flow of working fluid and operates in response to a difference in temperature between the measured storage tank temperature and the temperature of the collector surface on the roof.

Although the reliability of commercial solar hot-water heaters was not universally good when they were extensively deployed in the 1970s and early 1980s, today's systems are very robust, carrying warranties of 20+ years (see also section 13.6). Solar water heating was finally added to the US DOE "Energy Star" program for high-efficiency appliances. This technology also is suited to heating swimming pools, displacing the direct or indirect use of fossil fuels. According to the US Energy Information Agency (EIA, 2010), over 6 million solar hot-water systems have been installed in the US alone with a total added capacity in 2008 of 139 MW_{th}. They also report that solar pool-heating systems added 762 MW_{th} in 2008. As of 2009, China is adopting solar thermal water-heating systems on an increasing scale; about 10% of China's new building construction incorporates this technology.

Besides hot-water and pool heating, solar flat-plate systems can be used for space heating and cooling. In heating applications, air is often circulated through channels in the panels to capture the solar energy. It can then be used immediately for heating rooms by being forced through a set of room registers to distribute the heat or stored in a crushed-rock bed for later nighttime use. Alternatively, water can be used as the heat-transfer fluid in a similar manner—the only difference is that a set of room radiators would be used to distribute the heat. Air has an advantage over water in that it does not freeze or cause corrosion problems, but it has lower heat capacity and higher parasitic losses in distribution and storage systems.

For cooling, both vapor compression refrigeration and absorption cycles can be used. In a vapor compression cycle, solar energy can be used as a heat source to power a turbine in a closed-loop Rankine cycle, which, in turn, drives the compressor of the refrigeration cycle. A disadvantage of these cycles is that they need to be

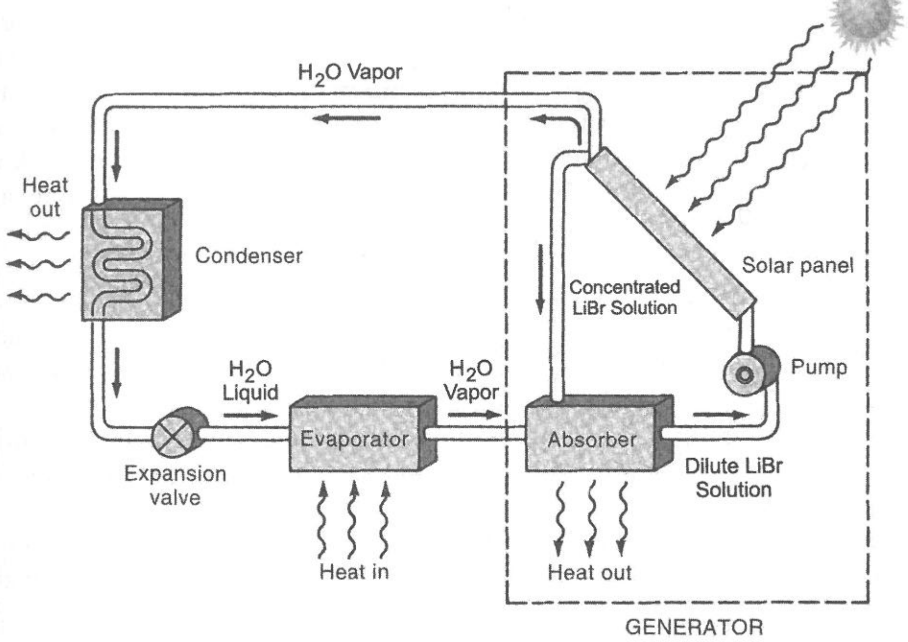


Figure 13.13
Flow sheet for a LiBr solar-powered absorption refrigeration system for air-conditioning applications. Adapted from Hinrichs (1996), p. 187, figure 6.35. © 1996 Brooks/Cole, a part of Cengage Learning. Reproduced by permission.

fairly large to have reasonable operating efficiencies. For both large- and small-scale cooling loads, a lithium bromide (LiBr) absorption cycle, shown schematically in figure 13.13, can be employed. Here, solar thermal energy at temperatures of 70–80°C is used to evaporate water from a low-pressure LiBr solution in the generator section of the cycle. The evaporated water vapor is cooled in the condenser and then reliquefied through expansion to vacuum conditions. This liquid water is revaporized in the evaporator section, again operated under vacuum conditions at about 40°C. The cycle is completed when the concentrated LiBr solution reabsorbs the water vapor from the evaporator.

13.3.4 Economic and policy issues

It is difficult to estimate costs for passive solar systems because they often become an integral part of a building's structure. For example, partial cost offsets result when a passive solar greenhouse, Trombe wall, or transpiring wall is incorporated into the design of a new building. In addition, guaranteeing trouble-free performance or other desirable attributes, such as enhanced daylighting, is as important as reducing heating costs in determining whether passive systems are deployed.

Although costs vary from location to location, a good average value to use for a roof-mounted solar hot-water system is about $20/ft^2 (based on 2008 markets), which includes the costs for the collector panels, piping, controls, storage tank with electric or gas backup heating, and installation. Solar air-conditioning units are a factor or two more than the heating system in capital cost. Assuming that a typical family-sized home in the US might need anywhere from 60 to 120 ft^2 of collector surface, an investment of $1,200–2,400 would be required. For comparison purposes for new construction, the installed cost of an electric hot-water heater would be less than $500. Of course, the tradeoff is between higher capital costs for the solar system versus higher operating costs for the conventional hot-water system.

Designs, and therefore costs, for solar space-heating units vary substantially depending on load and whether the system was integrated into the building structure, was external to the structure, or was retrofitted. Furthermore, an inherent problem with solar space heating is that there is a seasonal mismatch between the demand for heat and the availability of solar energy. When the demand is highest in the winter, the insolation levels are at their lowest values (see figures 13.6–13.8). Thus, having a means for seasonal storage of captured solar energy would enhance its value for space heating tremendously.

Several innovative concepts have been proposed for using the earth's subsurface in the form of water contained in a confined aquifer or as heated rock. While both of these concepts are technically possible, there are drawbacks. For example, additional costs are incurred to put such storage systems in place. Chapter 17 discusses some of the physical attributes of thermal storage that are relevant to implementing seasonal heat storage.

Given these limitations and constraints, deployment of existing passive and active solar heating and cooling technology has been severely limited by the high front-end capital costs that are incurred when a building is constructed. The potentially lower net life-cycle costs (amortized capital plus operating and maintenance costs) for a solar system may not be realized. The traditionally low prices of conventional fuels and baseload electricity—apart from occasional price shocks—is often the single most important factor that deflates interest in investing in energy efficiency and solar-energy capture.

There are several ways to make solar heating systems more attractive. Unit costs could be lowered by improving and scaling up production levels, and policy incentives could be introduced. The high capital cost of solar hot-water systems is partly driven by limited production and lack of standardization of performance. However, in spite of the 2006 economic downturn and slow recovery, solar thermal installations are continuing at a pace near 1,000 MW$_{th}$ per year. Introducing more incentives to homeowners or commercial building operators to install a solar system would also have an impact. Such incentives could take the form of tax credits or lower interest rates on mortgages or loans. Alternatively, building codes and standards could be revised to encourage the use of solar energy.

13.4 Solar Thermal Electric Systems: Concentrating Solar Power (CSP)

13.4.1 Fundamentals and options

Compared to the inherent simplicity of passive and active solar thermal systems for buildings, the use of concentrating solar energy for generating electricity is often perceived as a "high-tech" option. Even though the scale of most concepts for concentrating solar power (CSP) is much larger than a single home would need, much of the technology required for CSP is relatively mature and readily available for deployment. For a number of reasons, the current menu of CSP options has been divided into three types: power towers, trough systems, and dish-engine systems.

A few features are common to all of these options. Since solar energy is concentrated, the collector area is larger than the absorber area of the system. This concentration of energy yields much higher operating temperatures than those for flat-plate collectors. Steady-state temperatures range from about 400°C to above 1,000°C and provide an opportunity for generating electricity at reasonable thermal efficiencies or providing thermal energy for high-temperature industrial processes.

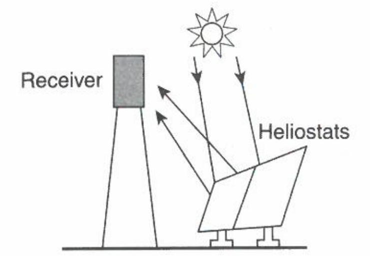
Because only the direct, unscattered portion of the solar spectrum can be accurately focused on the absorber, high-grade areas for CSP applications usually exist where cloud cover and atmospheric moisture levels are normally low and year-round insolation levels are high. This limits high-quality CSP sites almost exclusively to arid desert or semiarid regions at lower latitudes near the equator. In the US, the direct insolation resource is highest in the Southwest desert states of Nevada, Arizona, New Mexico, and southern California. Regions of southern Spain and northern Africa are also particularly well suited for CSP deployment. A recent parabolic trough installation in Andasol, Spain, has the first two units operating—each at 50 MW$_e$. This plant incorporates thermal energy storage in molten salt tanks with 7.5 hours dispatch capacity, almost doubling the annual operational hours of the power plant. Florida Power and Light recently built the first solar thermal hybrid facility connected to an existing combined-cycle fossil energy power plant—and the first US plant outside of the Southwest. At 75 MW$_e$, this solar plant will complement the dispatchable electric production of the existing plant and will displace some fossil fuel use.

In almost all cases, CSP plants produce only electricity by using some type of thermal energy to power the cycle. The incident solar flux is reflected and concentrated on a suitably designed absorber, where it is captured as thermal energy; this energy is then used in a thermal cycle to heat a prime mover fluid, such as pressurized water or compressed air, which is expanded to drive a turbogenerator unit for making electricity. Our coverage is limited to brief descriptions of each type of CSP technology in the subsections that follow. Those interested in pursuing CSP technology in more detail should consult the many available reviews and current websites for the latest information, for example DeLaquil et al. (1993) and the US DOE's Solar Energy Technologies Program website (www1.eere.energy.gov/solar/).

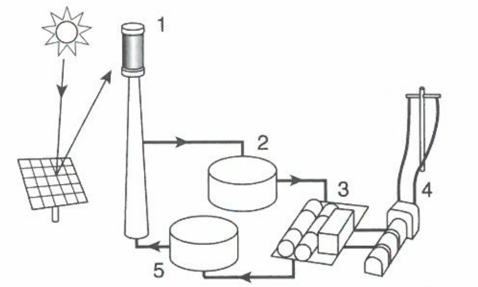
13.4.2 Power tower: Central receiver systems

A power tower system consists of a central receiver tower surrounded by a field of mirrors, or heliostats, which intercept and redirect incident solar energy to the receiver (as depicted in figure 13.14). Typically, such concentrated solar energy is absorbed into a high-temperature working fluid, such as a molten salt mixture, which is pumped through the absorber and stored for several hours at temperatures ranging from 500–600°C. A steam Rankine cycle is then used to generate electricity, with the working fluid providing the thermal energy needed to vaporize and superheat steam before expansion in a turbogenerator. Commercial power towers are large, baseload-type installations capable of producing up to 100–200 MW_e in a dispatchable mode when needed.

Several prototype, small-scale tower systems have been built and tested to demonstrate the concept. Notable demonstrations were conducted during the 1980s in Europe (e.g., Thémis at Targasonne, France; CESA and others at Tabernas, Spain) and Solar One and Two in the US, in the California desert at Daggett near Barstow. The Solar One and Two labels designate two separate phases of development in the US Department of Energy's (DOE) program. The Solar One experiment utilized about 71,000 m^2 of reflector surface with over 1,800 separate heliostats focused on a 55m-high water/steam receiver with an outlet design temperature of 516°C at 105 bar. The capacity was rated at 10 MW_e using an open steam Rankine cycle. Construction began in 1982 under joint sponsorship of the DOE, Southern California Edison, the Los Angeles Department of Water and Power, and the California Energy Commission. After two years of startup testing and upgrading, a four-year demonstration test was successfully conducted. The next phase led to the Solar Two demonstration, which was focused on improving the operability and dispatchability of the system by modifying the receiver, working fluid, and heat storage system. In place of the once-through steam system of Solar One, a mixture of potassium and sodium nitrate salts was used as the prime mover fluid in the Solar Two demonstration (see figure 13.14b). The change reduced the pressure of the receiver chamber

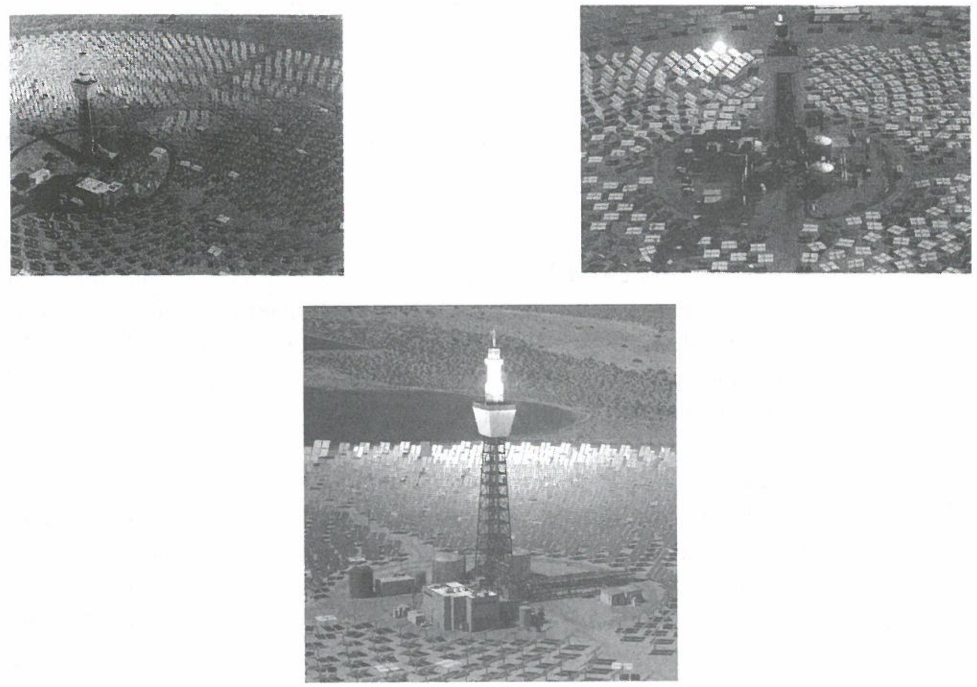


Large sun-tracking mirrors, called heliostats, focus the sun's energy on a receiver located atop a tall tower.



Schematic of electricity generation using molten-salt storage:
1) sun heats salt in receiver;
2) salt stored in hot storage tank;
3) hot salt pumped through steam generator;
4) steam drives turbine/generator to produce electricity;
5) salt returns to cold storage tank to be reheated in the receiver.

(a)



(b)

Figure 13.14
Solar power tower: (a) schematic of concept; (b) demonstration plant photographs. Sources: DOE (1996); Renne et al. (2002); SunLab (1998).

because water was no longer used, and allowed for thermal storage to be achieved at high temperatures (>500°C). In fact, the thermal storage capacity of molten salt systems of this type would permit continuous or dispatchable operations for periods of 24 hours or more, thereby increasing the value of the CSP-produced electricity.

Much has been learned about component performance for central receiver applications from the successes and failures that have occurred during the last 25 years of field testing, including improvements in the durability and ease of manufacture of mirrors, better heat-transfer design and materials and control systems for the central receiver itself, and demonstrated dispatchability using molten salt storage. These improvements have increased reliability, lowered parasitic losses, and increased efficiency to a point where engineers are confident of scaling up tower designs to commercial levels.

Nonetheless, a large capital investment is needed to build a power tower system. Even with the best projections available for 100–200 MW_e-sized systems, the lowest levelized busbar price for electricity produced in 2002 from central receiver power towers was about 8¢/kW_eh. In terms of capital investment, a range of $3,000–4,000/$kW_e$ is projected. Consider a 200 MW_e power tower facility. Here an investor would have to come up with $600–800 million to launch the project. In alternative energy markets, this magnitude of investment is not easy to realize and often requires national or international policies or subsidies, including loans, tax incentives, guaranteed prices, and production credits. Europe's first solar power tower, Planta Solar 10, and now Planta Solar 20, are operating in Andalusia, Spain, each with an installed 11 MW_e capacity. More than 200 MW_e are eventually planned for this area. These plants use superheated water storage (285°C and 50 bar) that corresponds to one hour of operation. Future plants may add molten-salt energy storage to extend the thermal storage capacity. Electricity from these plants is reported to cost about three times more than conventional power, so substantial subsidies of various types were needed to enable implementation of the projects. Spain has had a substantial feed-in tariff that encouraged such construction; it has been so successful that they instituted an annual cap of 500 MW_e in 2009.

13.4.3 Parabolic troughs

Trough concentrators reflect sunlight off a linear, parabolic mirror surface and focus it onto an absorber tube that is located along the focal line of the trough (as shown in figure 13.15). A heat transfer fluid, usually water or oil, is pumped through the receiver tube to heat it to temperatures ranging from 100°C to about 400°C. Parabolic troughs have concentrating factors between 10 and 100 and usually employ a one-dimensional tracking system to maintain proper focus on the fixed receiver tube as the sun moves across the sky during the day. The recovered thermal energy can be used for high-temperature process heat applications or as an energy source

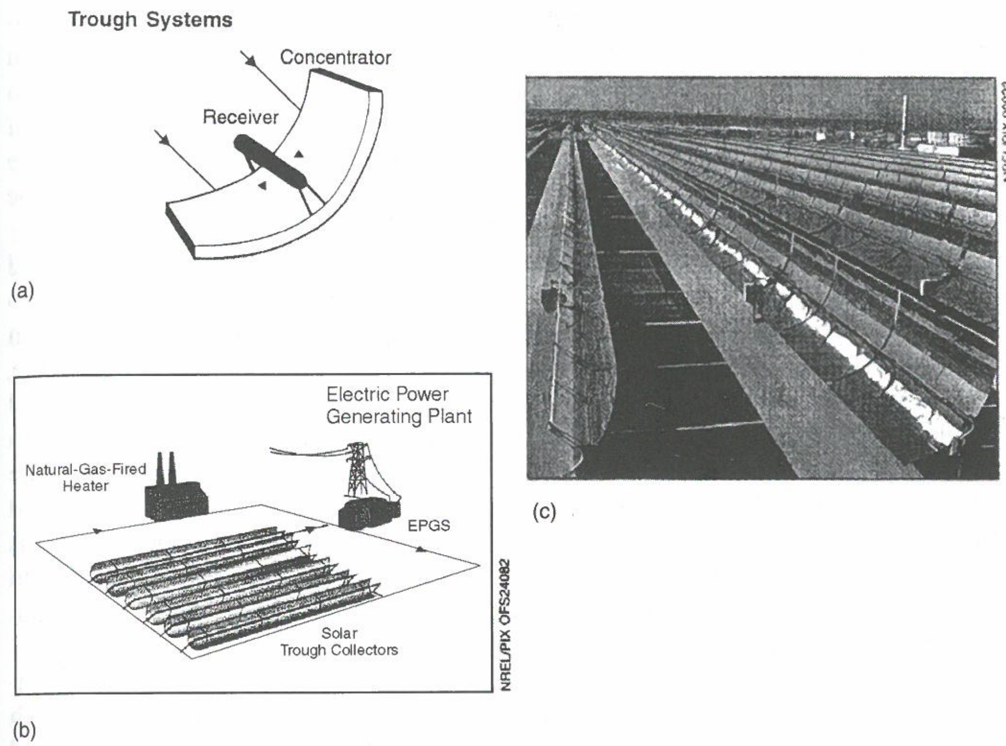


Figure 13.15
Parabolic solar trough: (a) schematic of trough concentrator; (b) dispatchable hybrid solar–natural gas system; (c) example. Sources: DOE (1996); SunLab (1998).

in a thermal electric power plant. Commonly, a conventional steam Rankine cycle is employed to produce electric power. Today's designs have achieved solar energy to electricity efficiencies of about 12%, including all parasitic losses associated with operating the collector system.

Trough systems have other desirable attributes that are worth mentioning. Each parabolic trough unit is modular and can be coupled to another for either series or parallel operation. Coupling units in series increases the operating temperature, while units in parallel operation achieve higher energy flows to feed a process or power plant. The generating capacity of a trough system for a single electric power plant ranges from about 10 MW_e to a maximum value of 200 MW_e. Since the solar energy source itself has a fairly low energy density, the land area needed for a trough unit is substantial. For example, in desert regions, where the total and direct normal insolation percentages are the highest, with about 2,500 kW_eh/m^2 of solar energy available annually, over 500,000 m^2 (0.5 square km) of collector surface area would be needed for a 100 MW_e plant operating with a 12% solar-to-electric efficiency. Another resource that may be needed is cooling water for heat rejection in the power plant. If evaporative cooling is employed, annual water requirements can be very high. For example, for that same 100 MW_e plant, about 1.5 million m^3 of water would be needed per year. Given that highest-grade CSP resources are located in desert regions, the consumption of cooling water is both an economic and a sustainability issue.

A mismatch normally exists between the time the solar energy is collected and the time the energy is needed; thus, storage may be used to permit the plant to operate in a dispatchable mode. Although some types of thermal storage (molten salts or heat transfer fluids) have been considered and tested, other types of storage, such as compressed air, pumped hydro, or magnetic energy storage, could be used if available. If hydropower is used as a backup, location might be a limitation because high-quality pumped hydro sites are usually quite distant from large-scale CSP locations in arid, desert regions. Alternatively, the plant may be hybridized with natural gas or another combustible fuel to provide thermal energy when it is needed and not available from the sun. Even without any storage, the plant would thus be fully dispatchable to supply power during periods of intermittent solar gain (e.g., when cloud cover exists) or during the night.

The receiver element of the trough concentrator is designed to maximize temperature while minimizing heat losses. Typically, an evacuated glass tube with a high transmittance surrounds a metal absorber tube that has been selectively coated with a high-absorptivity, low-emissivity material. With the best available technologies today (e.g., Luz cermets or Solel UVAC coatings), absorptivities of 0.92–0.96 and emissivities of 0.14 or less are possible.

Other losses occur in capturing solar energy with trough systems. These include reflectivity and transmission losses in the trough mirrors, tracking errors and shading losses, losses in transferring energy from the heat transfer fluid used in the receiver tubes to the prime mover fluid used in the process heat or electric power generator, and losses in storing heat.

Given that the major capital items in a trough system are mirrors and absorber tubes, several issues are being addressed to reduce costs. The modularity of trough components makes them well suited to achieve significant reductions in manufacturing costs as production levels increase. Current emphasis is on the use of low-cost materials that have high-performance characteristics, are durable, and are easy to fabricate and maintain in the field. The operating experience gained by deploying a number of commercial-scale systems in the 1980s and 1990s has been invaluable in moving the technology forward.

The history of troughs provides an interesting context for evaluating the potential of this technology form. Over 120 years ago, the first solar parabolic trough system was designed, fabricated, and tested by John Ericsson for supplying energy to an engine powered by a hot air cycle. Circa 1910, a 45 kW trough system was built in Egypt to generate steam power for operating irrigation system pumps (DeLaquil et al., 1993). After that early period, it took some time before working units were constructed for capturing and utilizing solar energy in a useful manner. The concern over energy resources in the early 1970s renewed interest in trough technologies. In stark contrast to solar power tower and dish-engine methods, troughs were actually built and have been operated at a commercial scale for over 25 years.

For example, in Chandler, Arizona, process heat for a copper electroplating plant is supplied by a 5,500 m^2 solar trough system. Another interesting thermal hybrid possibility is being explored at a coal-fired power plant near Grand Junction, Colorado. In 2010, a 4 MW_e parabolic trough CSP system was integrated with the existing 44 MW_e coal-fired plant. The CSP system heats tubes filled with mineral oil that then preheat the boiler feedwater for the power plant. The hybrid increases the power plant's efficiency by about 5% while reducing the CO_2 emissions from the plant by a similar amount, since the solar energy is displacing coal for the preheating. This first solar-coal hybrid will help evaluate the commercial viability of the technology for wider usage. Parabolic-trough solar is potentially useful for hybridization with many power systems. Integrated solar combined-cycle systems (ISCCS) are under construction in Egypt and Morocco; they use the solar heat to supplement waste heat from the gas turbine to boost power generation in the steam Rankine cycle. Integration to boost the efficiency of a geothermal power plant has been demonstrated in the US. Designs are being developed to integrate this solar thermal technology into future concepts for hydrogen generation.

At the Kramer Junction site in the Mojave Desert in southern California, there are nine separate solar trough electric plants operating with a total generating capacity of 354 MW_e. These are often referred to as the Luz solar electric generating system (SEGS) plants, named after the company that designed and built all nine plants. The SEGS plants range in size from 14 to 80 MW_e and have operating temperatures ranging from 325–410°C. The first plant (14 MW_e), built in 1984, and the last one (80 MW_e), built in 1990, incorporated many upgraded features that improved performance and lowered capital and operating costs. The first-generation Luz plants had a \$6,000/kW_e capital cost, compared to today's projected cost of about \$3,000/kW_e or less.

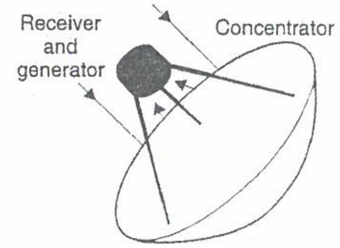
Natural gas was used as the backup in all nine plants, with no provision for thermal storage provided in SEGS plants 2 through 9. Public Utility Regulatory Policy Act (PURPA) regulations limited the maximum size of a plant to 30 MW_e until 1987, when the maximum was raised to 80 MW_e and eventually eliminated altogether. The nonsolar output of each plant was also restricted to no more than 25% of the total electricity generated. Without additional environmental offsets or green-power price credits, the existing level of investment tax credits granted and cost sharing of development costs with the DOE still were not enough to make trough-generated solar electric competitive with other alternatives, namely low-cost combined cycles fired by natural gas. Unfortunately, even with all nine plants operating, the Luz Company went bankrupt in 1991. The SEGS plants, nonetheless, continued to operate under new ownership and are still running today. Useful operating data and upgrades have been introduced, particularly to reduce O&M costs. The SEGS experiment underscores the need for subsidies and real operating experience to help bring down the cost of a new technology while increasing reliability and reducing risks.

Parabolic trough designs continue to develop. In the US, Nevada Solar One is operating with a capacity of 64 MW_e. In Spain, incentivized by favorable government policies, several large trough systems are being constructed. Andasol 1, operational since 2009, and Andasol 2 (50 MW_e each), still under construction in 2011, have additional molten-salt thermal storage which requires a somewhat larger solar collection area. A third unit is being planned. Each plant will produce more total power than the higher capacity Nevada Solar One plant because of its lower energy storage capacity. Another 50 MW_e project in Cordoba, Spain, just started construction in 2010.

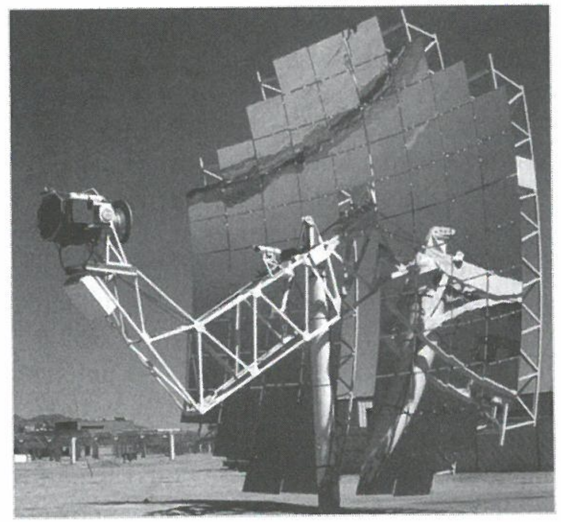
13.4.4 Dish-engine systems

The third major category of CSP technology is the parabolic dish receiver–heat engine generator. Here, direct solar radiation is concentrated by a factor ranging from 600 to 3,000, with a small number of focusing parabolic mirror reflectors aimed at a single absorber target located at the focal point. Heat is absorbed and directly applied to a heat engine generator that is mounted near the focal point (as shown in figure 13.16). A two-dimensional tracking system is used to point the dish to maximize the captured solar energy as the sun moves across the sky. Because of the high concentration ratios, absorber temperatures tend to be higher than troughs or towers, typically ranging from 600–1,500°C.

These higher collection temperatures, while potentially desirable for efficiently converting heat to electric power, introduce their own set of engineering challenges. One challenge is developing a means for removing the thermal energy from the absorber. Oil or water heat-transfer fluids have been used to accomplish this in several prototype systems. An alternative is to mount the heat engine at the focal point and to transfer the absorbed energy to the prime mover fluid without an intermediate step. Stirling cycle engines are good candidates for dish-engine applications because they use air as working fluid and can achieve reasonably high efficiencies for high absorber temperatures. Early tests of prototype models have achieved solar-to-electric efficiencies approaching 30%, which is higher than either



(a)



(b)

Figure 13.16
Solar dish-engine concentrator: (a) concept; (b) prototype example. Sources: DOE (1996); SunLab (1998).

today's trough or tower technology. In addition, gas-fired backup systems can be used to provide heat for the Stirling engine when solar energy is not available, which makes dish systems dispatchable in distributed applications. However, there are challenges, as operating lifetimes needed for reliable power generation have not yet been achieved, and installed capital costs are as high as those of the other CSP technologies. These issues pose significant barriers to commercialization. Trough and tower systems, which employ existing steam Rankine technology to generate electric power, can focus their cost-reduction development efforts on the solar end of the system (reflectors, absorbers, and thermal storage). In contrast, dish-engine systems require development of both solar and power converter components.

Dish-engine systems are sized in the 5–50 kW_e range, making them ideally suited for remote, distributed applications. They can be deployed and operated in a larger integrated system in much the same way as a wind energy farm. In January 2008, Stirling Energy Systems (SES) set a new solar-to-grid system conversion efficiency record at 31.25% on SES's Serial #3 solar dish system at Sandia National Laboratories' Solar Thermal Test Facility. Each dish unit consists of 82 mirrors, and the system produces up to 150 kW_e of grid-ready electricity.

With an appropriate scale for remote power generation, potential applications in remote regions of developing countries are providing momentum to push dish-engine technology along. Here, the value of having dispatchable electricity at a kW_e scale, albeit with associated higher unit costs per kW_e, outweighs the economic gains of operating large central-station power plants. Smaller units require smaller investments and avoid having to build the infrastructure needed to distribute power over long distances. Some believe that early deployment of dish-engine units in these remote, distributed niche markets will bring down costs and reduce risks enough to lead to larger-scale deployment in more competitive power markets.

13.4.5 Current status and future potential of CSP

The CSP technology portfolio has considerable diversity in both scale (from 5 kW_e dish engines to 100+ MW_e power towers and troughs) and application (from on-grid, central-station, baseload units to moderate-load, dispatchable plants to remote, distributed units). Table 13.2 and figure 13.17 summarize the characteristics and projected costs for solar technologies and the three types of CSP that were covered in this chapter.

Unlike other alternative energy technologies, there is over 20 years of operating experience in providing dispatchable electric power at a commercial scale at the solar-gas hybrid parabolic trough plants at Kramer Junction in California. The SEGS plants reduced O&M costs by introducing several innovations for replacing absorber tubes and for cleaning the parabolic mirrors. Nonetheless, like other

Table 13.2
Summary of Operating Characteristics and Estimated Costs for Concentrating Solar Power Technologies

	Parabolic Trough	Power Tower	Dish-Engine
Size	30–320 MW[a]	10–200 MW[a]	5–25 kW[a]
Operating temperature	390/734	565/1,049	750/1,382
Annual capacity factor	23–50%	20–77%[a]	25%
Peak efficiency	20% (d)	23% (p)	29.4% (d)
Net annual efficiency	11(d')–16%[a]	7 (d')–20%[a]	12–25% (p)[a]
Commercial status	Commercially available	Scale-up demonstration	Prototype demonstration
Technology development risk	Low	Medium	High
Storage available	Limited	Yes	Battery
Hybrid designs	Yes	Yes	Yes
Cost, $/m^2	630–275[a]	475–200[a]	3,100–320[a]
Cost, $/W	4.0–2.7[a]	4.4–2.5[a]	12.6–1.3[a]
Cost, $/$W_p$[b]	4.0–1.3[a]	2.4–0.9[a]	12.6–1.1[a]

Source: DOE (1997).
Note: (p) = predicted; (d) = demonstrated; (d') = has been demonstrated, out years are predicted values.
[a] Values indicate changes over the period 1997–2030.
[b] $/W removes the effect of thermal storage (or hybridization for dish-engine).

renewable technologies, there continues to be a large barrier to further deployment of CSP due mostly to their high capital costs. With proper policy instruments that consider a range of capacity scales and applications from large and small power markets, its environmental benefits, and its energy security, solar concentrators would be attractive for providing power in high-grade, arid, and desert regions where sustained high levels of direct normal insolation can be counted on throughout the year.

Connecting demand growth to CSP resource quality will also drive markets. For example, the continued growth in population in the southwestern US creates a real opportunity for supplying a portion of its growth in energy demands with CSP technologies. However, further work is needed on modular components, particularly heliostats and mirrors, absorber/receivers, and storage systems, in order to take full advantage of the cost reductions that will appear as production levels rise. For example, around 1996 the solar thermal manufacturing technology (SolMaT) initiative managed by the US DOE's SunLab focused on cost-reduction methodologies and started establishing ongoing research partnerships with industry. The prospects for lowering costs for key components look good. Numerous studies have indicated that, as production levels increase to 50,000 units with 150 m^2 units per year, the cost of two-axis tracking heliostats for power towers, including controls, could be reduced to about \$135/m^2 from a recent level of about \$200–250/m^2 (Teagan, 2001).

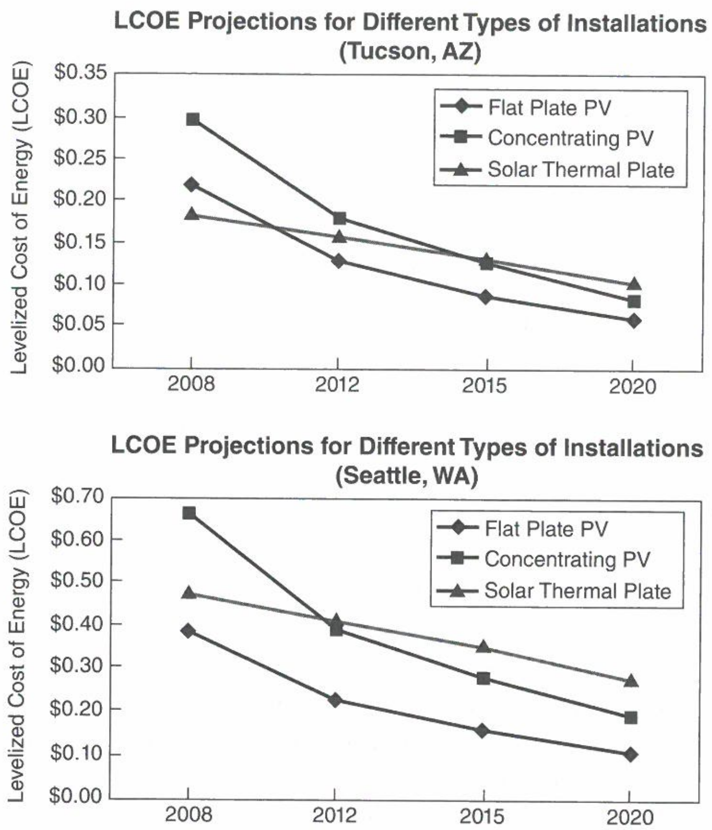


Figure 13.17
Actual and projected regional levelized electricity costs for solar power technologies in 2008US$. Data source: Solar Energy Industry Association, 2008.

The price had reached $126/m^2 by 2006, and the present goal is $100/m^2 (Kolb et al., 2007). Validation of this hypothesis will require a commitment to build and deploy several large central receiver plants to achieve these heliostat production levels. International collaborations, such as SolarPACES, also provide considerable leverage to support key R&D and demonstration projects focused on common objectives for improving CSP technology and reducing costs.

Other ways of using concentrated sunlight for energy applications are also being considered. These include buildings integrated with trough technologies for providing heating and cooling needs with enhanced daylighting (Myles, 2002) and concentrating photovoltaics (see section 13.5.6). A distinct advantage of these proposed applications is that they are small in scale (10 kW) and do not need to be located in the highest-grade insolation regions.

13.5 Solar Photovoltaic (PV) Systems

Photovoltaic (PV) devices utilize the photoelectric effect in semiconductor materials to convert solar energy directly to electricity. Although the basis and proof of the concept were in place in the mid-nineteenth century, actual PV devices were not developed until the 1960s, when they were motivated in large part by the US and Soviet space programs. The first practical PV cells were constructed of crystalline silicon and were very expensive, costing upward of $250/W$_e$ (or $250,000/kW$_e$) at that time. At this stage, PV technology was not suitable for large-scale terrestrial power applications. Following their use in space exploration, other applications appeared. As manufacturing technology and experience expanded, prices dropped into a range where PV units could be used to replace nonrechargeable batteries. Starting in the 1970s, PV devices were developed for watches, calculators, road signs, remote communication systems, and similar applications. Small-scale (1–100 kW$_e$) power-generation applications began to surface in the late 1970s as well, when PV module collectors for building applications appeared in the marketplace. The growth in module production, primarily crystalline silicon, has been steady at about 15–20% per year for the last 25 years or so. By 2003, over 700 MW$_e$ of solar cells were manufactured at costs at that time of $2,500/kW$_e$ or less, which represents more than a 100-fold reduction in module price. In 2010, costs are continuing to decrease and are now close to $1,000/kW$_e$. When other components that comprise the entire PV system are included, the total cost per kW$_e$ is about twice the module cost. In 2002, entire PV systems that included polycrystalline silicon modules, power inverters to produce alternating current (AC) from direct current (DC), other power conditioning and control equipment, and a modest battery storage system could be installed at prices ranging from about $600 to 900 per m^2 of active collector surface. 2010 prices were in the range of $500 per m^2 for a typical system. Developing improved manufacturing methods for modules and associated PV equipment to bring costs down has become a major focal point of the PV industry. (We will say more about the costs and values of PV systems in section 13.5.6.)

PV systems are attractive because of their simplicity. They have no moving parts. They are noise-free and potentially have low maintenance requirements. Moreover, PV systems have built-in modularity and are scalable for applications ranging from watts to megawatts, and they can be integrated directly into the unit they are providing power for, whether it is a remote highway sign or residential dwelling.

The sections that follow provide a brief overview of PV technology. First, we review the basic concepts of photovoltaic cell operation and key performance and technology issues that are common to all types of cells. Next we focus on the major types of systems being developed and deployed worldwide—crystalline and amorphous silicon, thin-film copper indium diselenide (CIS), and cadmium telluride

(CdTe)—reviewing what is unique about each and the status of its development. In the final section, we discuss more advanced concepts and summarize the prospects for PV.

The popularity and scientific elements of engineering materials for photovoltaic applications have resulted in a rich field of technical literature on the subject. For more depth and details on PV technologies, readers are directed to a few archival references, as well as to the website resources listed at the end of the chapter. In particular, reviews worth examining appear in *Annual Reviews of Energy and the Environment* and in articles in the edited volume *Renewable Energy* (1993), authored by Kelly, Green, Carlson and Wagner, Boes and Lugue, and Zweibel and Barnett; also illuminating are numerous publications by the National Center for Photovoltaics, located at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, and the solar electric utilization research carried out by the US Department of Energy's Basic Energy Sciences (BES) (at http://www.science.energy.gov/bes/efrc/centers/unc/).

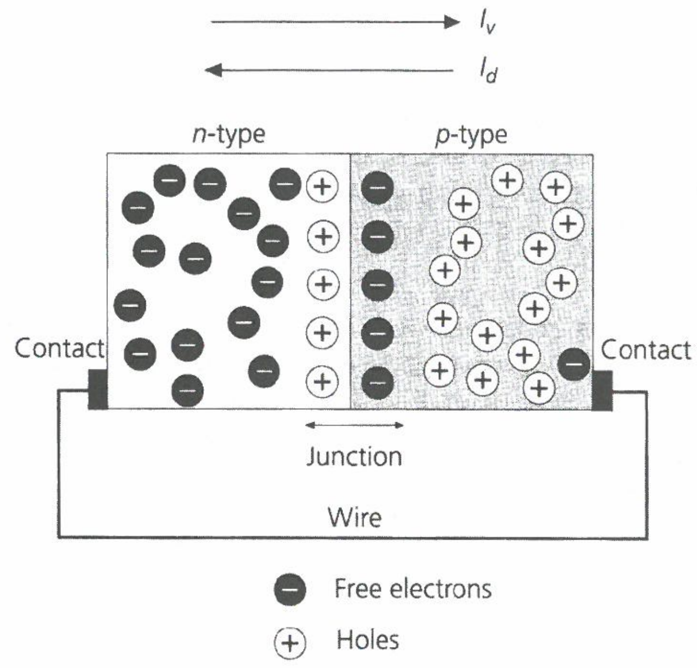
13.5.1 Solid-state physical chemistry fundamentals

The photoelectric effect is the underlying phenomenon that controls how a photovoltaic device converts sunlight directly into electrical energy (Nelson, 2003). When a photon strikes certain materials, such as conductive metals and semiconductors, the material's electrons are able to "capture" the photon's quantized energy. If that energy is of sufficient magnitude, exceeding the so-called band gap of that material, then electrons are promoted to excited states. In a PV device, an excited electron must be withdrawn before it relaxes. The PV device actually works by creating a voltage difference within a nanoscale structural environment that directs the migration of electrons to produce a current. This is achieved by arranging certain semiconductor materials in a prescribed manner. Typically, p-type and n-type semiconductor materials are electrically connected, as illustrated in figure 13.18.

The n-type, or negative, material is one that allows electrons to move freely within it. Thus, the current carriers in an n-type material are electrons. Silicon becomes an n-type semiconductor when small amounts of impurities, such as phosphorus, are added to it. In scientific terms, such n-type silicon is "doped" with phosphorus.

The p-type, or positive, material operates in an analogous but opposite manner. If a different impurity, such as boron, is added to silicon, a portion of the electrons associated with silicon are "tied up" or partially immobilized by the presence of boron atoms. This creates a network of "holes" within the silicon crystal that are locally positively charged. These "holes" act as if they were positive charges and serve as current carriers in an analogous manner to the free electrons in an n-type material.

(a)



(b)

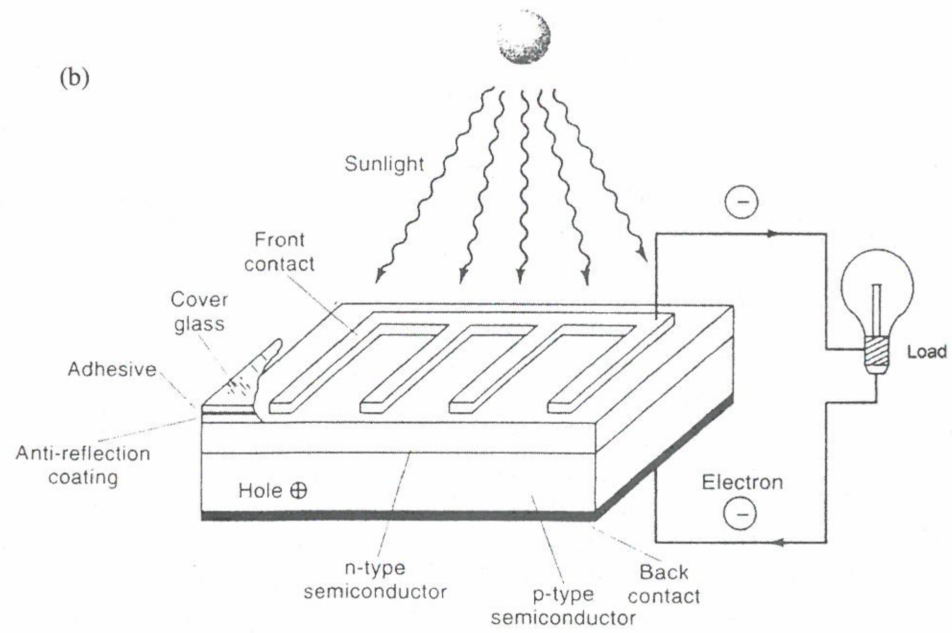


Figure 13.18
A p-n photovoltaic semiconductor device: (a) p-n junction, contacts; (b) circuit schematic. Sources: Kelly (1993); Renne et al. (2002).

Since n- and p-type materials allow the selective transport of either electrons (n-type) or holes (p-type), interfacing the two materials allows photogenerated electron-hole pairs to be separated. Placing an n-type material in contact with a p-type creates a p-n junction (as shown in figure 13.18a), which has certain properties that are altered by the presence of light. First, without light present, the electrons of the n-type material tend to migrate across the junction to form a locally high concentration in the p-type material near the junction. Similarly, this creates an excess of holes, or positive charges, in the n-type material adjacent to the junction (see figure 13.18a). These processes lead to a small voltage difference across the junction. For silicon-doped materials, this amounts to about ½ volt. The charge gradient creates a small current (I_d), which is exactly balanced by a current (I_v) resulting from the thermally activated effects that release a small number of electrons and holes.

Without light present, there is no net current flow through the p-n junction. When sunlight strikes the PV device (as shown in figure 13.18b), the photoelectric effect causes the number of free electrons in the n-type material to increase and the number of holes in the p-type to increase as well. Connecting the two different materials across a load, using the electrical contacts shown in figure 13.18b, causes electrons to flow from the n-type material through the load, where they deposit measurable electrical power and then recombine with the excess of holes in the p-type material to close the circuit.

In figure 13.18b, we see how things are arranged for a typical silicon solar cell. Metal contacts with a large fraction of open area for light to enter the module are attached to the front surface of a thin layer (about 1 μm) of n-type material. The bottom layer of p-type silicon is normally thicker (typically from 100 to 400 μm) and coated with a metal material that provides both structural rigidity and electrical contact. Although most PV devices have features similar to those found in silicon cells, there are differences (as will be discussed in the sections that follow).

13.5.2 Performance limits and design options

The key performance metric of any photovoltaic system is the net efficiency of converting sunlight to electricity. For a given amount of insolation, the required collector area to meet a given load decreases directly in proportion to an increase in efficiency. There are several measures of efficiency. The highest values reported are almost always obtained under well-controlled conditions in a laboratory with small cells, often using artificial sunlight as a calibrated energy source. The next level lower is measured for individual PV modules, again under controlled conditions. The final level is measured for complete PV systems installed in the field.

Under intense sunlight at peak periods, the solar flux to the surface of a cell is on the order of 1 kW$_e$/m^2, which produces a current of about 100 mA/cm^2 at a solar-

Table 13.3
Representative Photovoltaic Cell Efficiencies as a Percentage of Incident Solar Insolation to Electricity

Type	Field-Deployed Modules (%)	Prototype Modules (%)	Lab-Scale Experimental Cells (%)	Theoretical Limit (%)
Flat-plate				
Single crystalline silicon (Si)	10–12	16–18	24+	30–33
Polycrystalline silicon	8–9	—	18.2	—
Single-junction amorphous silicon	3–5	5	6–8	27–28
Multijunction stabilized amorphous silicon	8	10	12	27–28
Copper indium diselenide (CIS)	—	11	14.8	23.5
Cadmium telluride (CdTe)	—	10	15.8	27–28
Stacked multijunction amorphous silicon and CIS	—	—	15.6	42
Concentrators				
Gallium arsenide (GaAs)	NA	22	28	—
Gallium arsenide and antimonide (GaAs and GaSb)	NA	NA	34	—
Two-junction, two-terminal, monolithic	NA	NA	30	42+
Three-junction, two-terminal, monolithic	NA	NA	32	42+

Sources: NCPV (2002); Kelly (1993).
NA: not available.

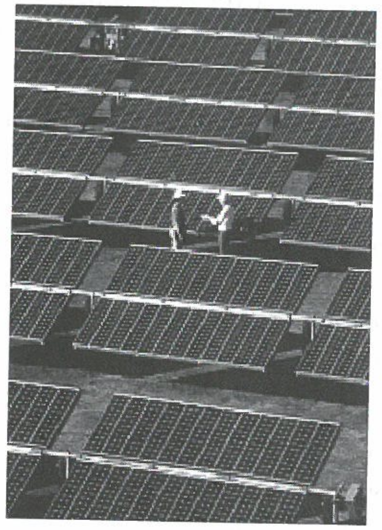
to-electric energy efficiency ranging from a few percent to over 20% depending on a number of factors. Table 13.3 lists typical values of efficiency for a range of PV cell types. Important factors affecting efficiency include the following:

1. loss of energy above the band gap of the material and the inability to capture IR energy below the band gap;
2. reflective losses off the top surface of the PV collector;
3. loss of effective interception area due to the presence of the metal contacts on the top surface;
4. ineffectiveness of photon-electron interactions in the layers of n- and p-type materials;
5. ohmic resistance losses in the circuit;
6. recombination of electrons and holes before reaching the p-n junction;
7. required band-gap energies limiting the ability of photons at low energy levels to create free electrons and holes.

The durability of the module itself is also a key issue. Given that capital costs are high, PV systems should be able to run essentially maintenance-free for long periods—10 to 30 years are expected lifetimes for applications in competitive energy markets. As a result, the ability to maintain efficiency and resist the degrading effects of exposure to weather is essential for building deployed PV systems. While flat-plate PV devices utilize both direct and diffuse sunlight, different PV devices have different capture and conversion efficiencies that vary with the intensity of light and its wavelength or frequency within the solar spectrum (see discussion below and figure 13.1).

The performance of the PV module itself is centrally important. Nonetheless, there are several other components in the system that must perform well and not cost too much. These are often referred to as "balance-of-system components." They include power connections, power conditioning (e.g., inverters), control and interconnection equipment, and, in many cases, an electrical storage system usually consisting of batteries (see chapter 17).

PV collectors fall into one of two categories: flat plates or concentrators. Concentrating the direct light is viable economically only if the cost of the cell or the absorber material is sufficiently high to justify the additional cost of the optical system. By far, flat-plate configurations represent the largest fraction of manufactured and installed systems. Figure 13.19 shows the two common options for deploying flat-plate PV systems—as roof-mounted units and as modular units within a



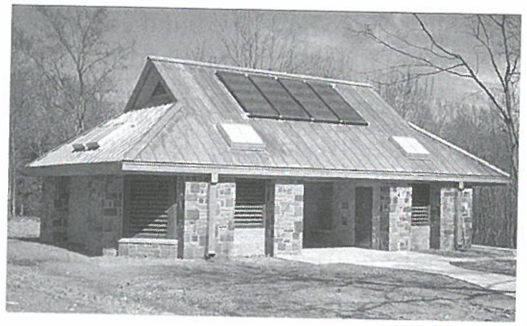


Figure 13.19
Photographs of typical PV installations. Sources: Renne et al. (2002); SunLab (1998).

separate structure. While flat-plate systems utilize solar cell material over their entire exposed area, the interception area of a concentrator employs lower-cost mirrors or lenses to focus the sun's energy on a smaller area of a PV device. This approach, in principle, leads to both increased performance of the PV device and lower costs because less semiconductor material is needed for each module. However, concentrators only utilize the direct, unscattered portion of the solar spectrum, which reduces their versatility over flat-plate systems.

Regardless of which collector approach is used, the motivating principle of all PV technology development is to lower capital and operating costs per $kW_e h$ generated. For flat-plate technology, costs are lowered by increasing module performance (higher efficiency requires smaller areas; and higher reliability requires less O&M) and by decreasing module manufacturing costs. These costs are lowered by reducing the amount of highly refined semiconductor material needed by utilizing thin films or by increasing productivity per unit time. Most current R&D centers on lowering manufacturing costs without sacrificing efficiency and reliability. For concentrator systems, not only must the solar cell be optimized, but other critical components, such as the tracking system and reflectors, require careful attention in terms of performance and cost.

Keep in mind that the module typically represents about 50–60% of the total capital cost. Other balance-of-system components, such as DC to AC inverters, interconnection devices, control and storage systems, and installation itself all are important and need to be considered in any attempt to reduce cost. Balance-of-system elements alone currently add up to about $2,500/$kW_e$ installed for roof-mounted PV units retrofitted on buildings.

13.5.3 Silica-based systems (crystalline and amorphous)

As of 2009, about two-thirds of PV installations utilized crystalline silicon, but the share of thin-film technologies is steadily increasing (EIA, 2010). The main tradeoff between using single crystalline versus polycrystalline silicon is one of efficiency versus manufacturing cost. Single crystals of silicon have the highest efficiency, about 2–3% higher than refined polycrystalline material, but their manufacturing costs can be many times higher than those of polycrystalline modules. As a result, most non-space (commercial) PV applications use polycrystalline silicon devices that are produced as thin wafers cut from cast ingots or drawn as a thin ribbon from molten silicon. The cost of producing the solar cell is in direct proportion to the amount of silicon used, divided between the raw material cost and the cost of the energy needed to refine and process the silicon.

An alternative to using single or polycrystalline silicon was proposed in the 1970s. The basic idea was to deposit a thin film of noncrystalline, amorphous silicon directly on an inexpensive support material. Because of the excellent solar absorption characteristics of amorphous (a-) silicon, films with a thickness of only 1μm or less (compared to the 200–300+ μm needed for crystalline cells) would be required. Thus, manufacturing lines could be configured to produce solar cells by a continuous highly efficient process (see Carlson and Wagner, 1993, for details). There are a few drawbacks. The major problem is that a-silicon cells have lower efficiencies (see table 13.3), and they can be unstable, with decreases in efficiency appearing after a short period of operation. These issues are being addressed in a vigorous worldwide R&D effort, and much progress has been made. Figure 13.20 illustrates the progressive improvements in stabilized device efficiencies that have been achieved. This is remarkable given that the first a-silicon cells of 1974 had efficiencies of only 1% (Carlson and Wagner, 1993). Today, the major development effort also is focused on reducing manufacturing costs. Continuing innovation includes recent development of a tandem cell (see www.oerlikon.com/solar/) which significantly boosts solar cell efficiency by adding a second microcrystalline absorber later to the amorphous silicon (a-Si) layer. This second layer converts the energy of the red and near-infrared spectrum, facilitating efficiency increases of up to 50%.

13.5.4 Copper indium diselenide (CIS)

In the search for lower-cost PV devices, materials that have similar optical properties to silicon but lower energy intensity (and production costs) are being investigated (Wadia, Alivisatos, and Kammen, 2009). Semiconductor PV devices consisting of 1–3 μm layers of copper indium diselenide ($CuInSe_2$ or CIS) along with comparable thin overlayers of silica (SiO_2) and cadmium zinc sulfide (CdZnS) or cadmium sulfide (CdS) have somewhat higher efficiencies than a-silicon devices (see figure 13.20) and are predicted to have similar manufacturing costs (see Zweibel and Barnett, 1993, for details). Again, much of the R&D effort is concentrated on simultaneously improving the electro-optical properties and durability of the films while streamlining the manufacturing process to reduce costs. This is particularly challenging because the process requires deposition of these films in a clean, high-vacuum environment similar to that used to manufacture today's computer chips. The big difference with thin-film PV versus computer chip manufacture is that large volumes must be produced at very low cost.

Developing CIS cells on a large scale has sustainability and toxicity concerns that must be addressed. For example, workers involved with their manufacture need to be protected. Also, the impacts of extracting required elements (Zn, In, Mo, Se, Cd, and Cu) from natural mineral resources may create regional supply and demand constraints, and the environmental damage associated with mining and refining operations, as well as with end-of-life disposal, will need to be minimized.

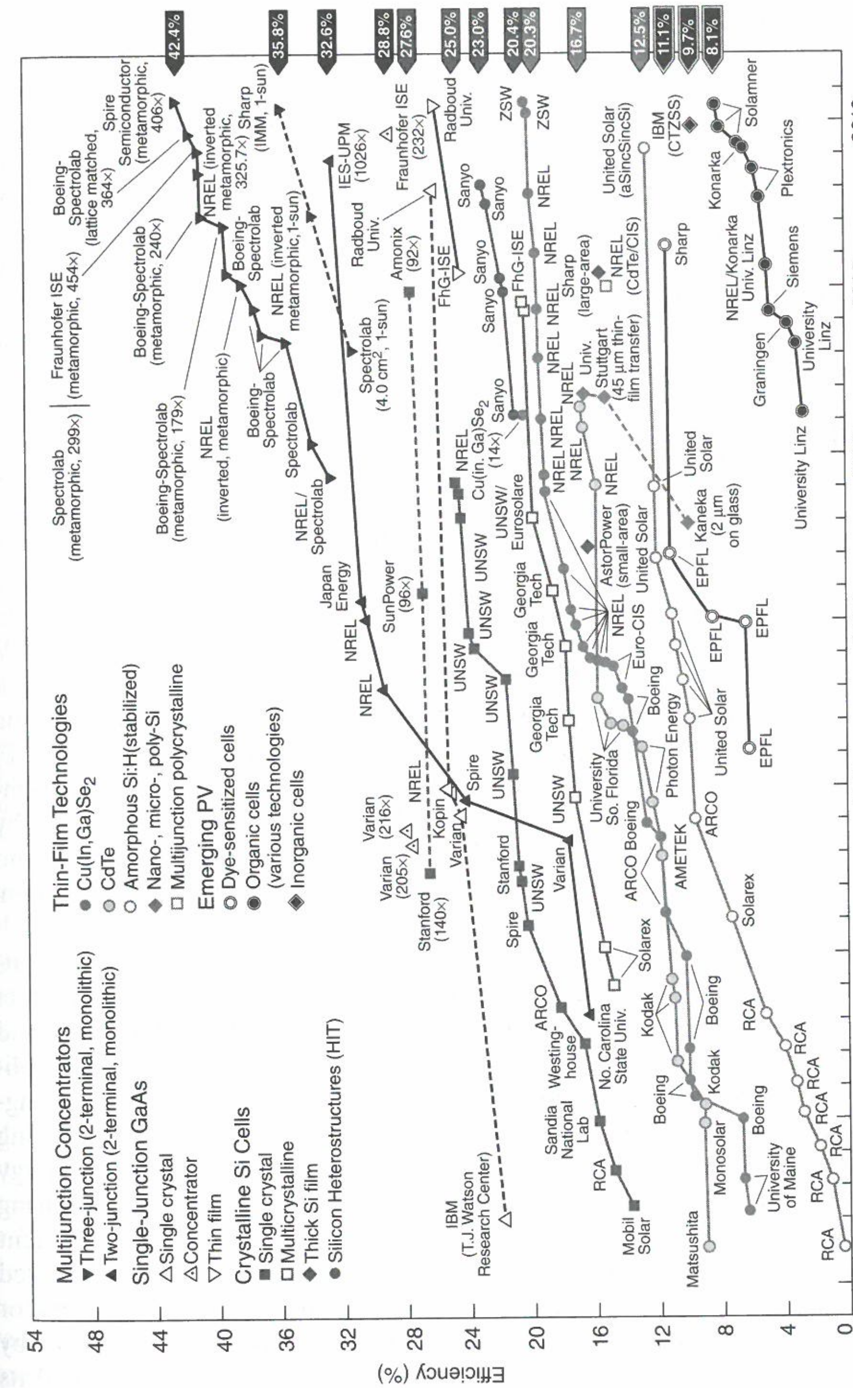


Figure 13.20
Thin-film and multijunction photovoltaic cell efficiencies. Source: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg (accessed December 2011).

13.5.5 Cadmium telluride (CdTe)

Another popular thin-film candidate is CdTe. Its band-gap energy of 1.5 eV is nicely matched to the solar spectrum, with predicted theoretical efficiencies of 27–28% (see table 13.3). Since its discovery in the 1950s, laboratory device efficiencies have improved from a few percent to over 16% (see http://www1.eere.energy.gov/solar/sunshot/; Zweibel and Barnett, 1993). A number of manufacturing options exist for CdTe systems, including electrochemical deposition, which could lead to significantly lower module costs. The same concerns about toxicity, resource consumption, and waste contamination exist for CdTe as for CIS systems. Nevertheless, continuing improvements in CdTe technology are leading to growing sales and commercialization.

13.5.6 Current status and future potential of PV

There are a number of options for PV systems, each with its pluses and minuses. The performance and cost of the four major technologies—polycrystalline wafers and ribbon, and thin films consisting of *a*-silicon, CIS, and CdTe—have been improving for the last 20 to 30 years as production has increased (see figure 13.21). Since the mid-1970s, installed costs for rooftop flat-plate PV systems have dropped from \$30,000/kW$_e$ to about \$4,000/kW$_e$ in 2010, with reductions in manufactured PV module costs making the biggest contribution. Innovative collaborative work between government and industry has accelerated improvements to manufacturing processes for PV systems. For example, the PV Manufacturing Technology (PVMaT) program managed by the National Center for Photovoltaics (NCPV) and sponsored by the DOE has followed a practical roadmap for bringing down costs by focusing on critical manufacturing issues. (Figure 13.22 shows both achieved and predicted cost reductions that have resulted from the successful PVMaT campaign. Recent data in 2010 confirm its success.)

A positive attribute of PV technologies in general is the opportunity for integrating the PV collector system into the building structure itself. Given that both direct and diffuse light can be converted to electricity, the external walls, windows, and roof of any structure could, in principle, be turned into a PV collector. Some policies in the US, Europe, and Japan are encouraging the *development* of building-integrated PV systems, as well as the installation of roof-mounted units, by offering subsides, tax incentives, or "green" energy production credits. As a symbol of energy conservation, President Carter had PV panels installed on the White House during his presidency; they were later removed by President Reagan. In 1997, President Clinton announced a major deployment initiative for solar energy in the US, called the "Million Solar Roofs" initiative. The basic idea was to place one million PV or solar heating systems on the rooftops of American residences and businesses by 2010. In 2004, California took on the flagging national program and installed its

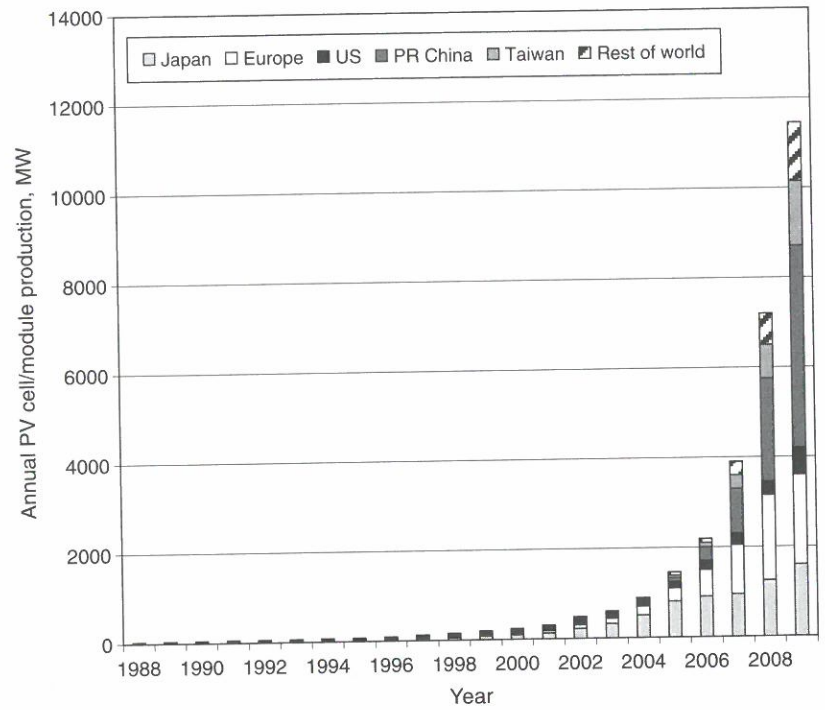


Figure 13.21
History of PV module production worldwide from 1988 to 2009. Note: World production in 1988 was 33.6 MW$_e$; in 1993, 60.1 MW$_e$; in 1998, 153.2 MW$_e$. Source: JRC (2010).

first units in 2007. Five years later, the Million Solar Roofs initiative was one-quarter of the way toward its goal of installing 3,000 MW$_e$ of distributed solar energy systems by the end of 2016—putting the program on a pace to meet the overall goal on schedule. As late as 2011, President Obama's efforts to reinstall PV panels (and solar thermal water-heating systems) on the White House as an example of his commitment to renewable energy are still in the planning stage.

In order for large gains to be achieved in the deployment of PV systems, more attention must be paid to critical balance-of-systems issues, especially electrical energy storage and interconnection standards and equipment. Reducing costs, while increasing performance and reliability, are key elements. While national policies will assist the process, a long-term commitment to R&D is required to develop new devices, encourage manufacturing process improvements, and create a set of uniform codes, standards, and testing procedures for components and complete systems to reduce risks and build a consumer base. On the research side, the most advanced tools of basic scientific research must be applied to the problems of producing

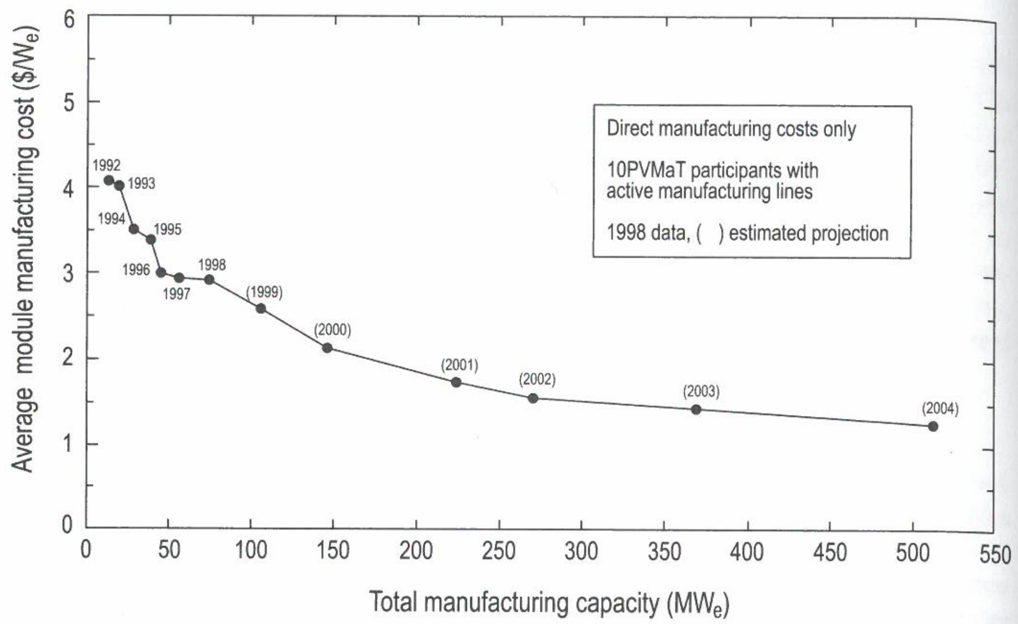


Figure 13.22
Potential cost reduction as a result of the US-led PVMaT initiative. Note: In 2010, the actual module manufacturing cost was close to 1¢/W_e. Source: DOE (1996).

low-cost, reliable PV systems. Of the numerous examples that illustrate basic research programs that could lead to significant gains in PV development, we have chosen two to describe in detail here.

The first example uses thin-film, triple-junction semiconductors to engineer the PV device on a molecular level, optimizing both the absorption and conversion of photon energy into electricity. Recent collaborative work by Spectrolab and the National Center for Photovoltaics has produced efficiencies of >40%, the highest ever for a triple-junction PV. In this case, an optimized device results from using three connected layers of gallium indium phosphide, gallium arsenide, and germanium (see Staedter, 2002, for details).

The second example is the development of a solar power window that produces PV electricity from the infrared and ultraviolet portion of the solar spectrum while transmitting visible light into the structure to achieve daylighting. Researchers at NREL (A. Frank, personal communication, 2002) are pursuing this idea by utilizing a dye-sensitized PV cell—the so-called Gratzel cell, which was invented at the Swiss Federal Institute ETH in the early 1990s.

The search for alternative low-cost solar cell materials is a subject of intense worldwide research investigation. It is impractical to review this rapidly evolving

work thoroughly here; several good reviews have been published (Materials Research Society, 2007; Hoppe and Sariciftci, 2004; Nozik et al., 2010).

13.6 Sustainability Attributes

The desirable features of solar energy include its inherent flexibility and range of scales for many applications. Uses range from 1–10 kW_e-scale passive and active heating and cooling systems (integrated into the designs of individual homes) up to 10–200 MW_e-scale concentrating solar power towers and troughs that generate dispatchable electricity tied into a national grid.

Considering ways to capture and utilize a portion of the solar spectrum that intersects the walls, roof, and windows of a building in order to meet a portion of heating, cooling, lighting, and other electricity needs is intriguing from a sustainability perspective. Currently, about one-third of our annual energy budget is used to condition and maintain the buildings we live and work in (see chapter 20 for further discussion). Much of the time, we consume energy to offset the effects introduced by the conditions of the day or season (e.g., heating in winter and cooling in the summer, providing light when it is dark). To a large extent, the sun's presence or absence is responsible for creating this demand for energy. Many argue that by capturing, storing, and converting solar energy into usable heat or electricity, we are achieving a sustainable energy system. Unfortunately, this rationale is too simplistic, as it does not consider the full life-cycle elements of performance, the environmental impacts, nor the costs involved in constructing and maintaining solar energy systems.

The hardware and the space it takes to concentrate, convert, and store this intermittent and dilute energy resource carry their own environmental and economic burden. Consider the embedded energy content of a silicon PV module constructed with polycrystalline wafers. Rough estimates indicate that it takes about two years of operation for the silicon PV collector to recover the amount of energy that was needed to manufacture it. In fairness, the newer thin-film PV concepts currently being pursued require much less energy to manufacture. Solar hot-water heaters and passive Trombe and transpiring walls also quickly recover their embedded energy content. In any case, the needs for energy, materials, and other natural resources in the manufacture and maintenance of each solar energy system should be evaluated.

Other environmental and health concerns for advanced PV systems arise from the types of materials being considered, such as CdTe and $CuInSe_2$ or GaAs. Many of these are toxic in several chemical forms, and the processes associated with recovering, purifying, and utilizing these materials carry their own impacts. The abundance and availability of materials are also important issues, particularly for tellurium and CdTe solar cells (Wadia, Alivisatos, and Kammen, 2009). Nonetheless, the use of thin-film technology for these PV applications has greatly reduced the amounts of semiconductor materials needed. Furthermore, the improved durability and reliability of today's PV systems, which have extended service lives to 25 years or more of operation, suggest that resource consumption and the associated contamination of the environment may be much less severe than originally thought.

Solar energy is a renewable resource that requires matching of the solar resource grade in a particular region to the demand for heat or electric power. While gaining access to the sun is relatively easy in remotely populated regions or for homes in suburban America or other locations, there are substantial challenges in using solar energy to provide a large fraction of the energy needs of a megacity like New York or Tokyo. In these cases, the transmission and distribution of solar energy from the point where it is captured to where it is used must be addressed. In addition, because it is inherently intermittent and variable on an hourly and seasonal time scale, storage of electricity and/or heat will be necessary in most solar energy applications.

The land required for large-scale solar electric installations is another environmental impact that must be dealt with. A few comparisons provide a basis for evaluation. Recall the amount of land associated with a typical large hydropower project (chapter 12) or what is needed to cover the entire fuel cycle requirements of a bioenergy (chapter 10) or strip-mined coal supply and conversion operation (chapter 8). A CSP plant in the southwestern US desert would need about 20 square miles of land to produce roughly the same average amount of electricity as generated by the Hoover Dam annually; yet the inundated portions of land behind the Hoover Dam (forming Lake Mead) amount to about 250 square miles, over 10 times as much area. A key siting issue for CSP has to do with the height and brightness of large central receivers on power towers. For unit sizes over 100 MW_e, the receiver heights will be 200 m or more.

During the ambitious deployment period of the 1970s and 1980s, reliability and durability problems plagued active solar systems. With tax incentives in place and growing customer demand for solar water heaters and PV panels for home use, many new companies were formed that focused on manufacturing components and assembling and deploying integrated products. Unfortunately, a large fraction of them were not able to produce a reliable product. In 1984, over 250 manufacturers in the US sold more than 1.5 million m^2 of collectors, but by 1990 over 200 of these manufacturers had gone out of business, with the solar water-heater market eroding to less than 0.5 million m^2 per year (Brower, 1992). To make things worse, poor choices of materials, inadequate control systems, and shoddy workmanship on site led to frequent failures and distrust in solar technology. By 2000, with reliable solar products available, annual sales in the US increased again to a stable level of about

1 million m^2 per year without strong policy or financial incentives. A similar trend has occurred in Europe, with a few important exceptions. Israel, Australia, and Cyprus have seen growing markets and increased penetration of solar technology, driven largely by two factors: a high-quality solar resource and favorable policies. At the start of the twenty-first century, national subsidy programs in several European countries and Japan have led to aggressive PV deployment programs. In 2009, subsidized growth was sufficient to begin a slow phase-out of some of the subsidies. Germany reduced the amount of its feed-in tariff by 10%, and Spain capped new capacity subsidies by their feed-in tariff to a maximum of 500 MW_e per year. China and Taiwan are also pursuing aggressive implementation of these technologies. Solar technologies are thus being deployed successfully globally and, although growth may slow for a while, the solar industries are finding their economic niches and learning to expand them.

13.7 Summary and Prognosis

To capture and efficiently utilize the sun's energy in today's energy markets requires multiscale integration of several factors, including proper matching of the solar resource and energy demands of a particular region, workable distributed energy systems with robust transmission and distribution and functional interconnection, a means for storing heat, and policy incentives that encourage the use of solar energy as a renewable resource. Given that the capital costs of solar energy systems are high relative to those of fossil fuels, financial restructuring of energy markets will be needed to place additional value on the attributes of solar energy over lower-priced depletable fossil-energy alternatives. These values include the absence of emissions and solar power's frequent coupling to energy-efficiency technologies that reduce consumption per unit of energy service provided, which are all linked to increasing sustainability indices.

In many ways, the inherent flexibility and simplicity of passive and active solar systems help to produce energy-efficient buildings that are affordable and desirable. The benefits of solar systems are substantially enhanced when coupled to advanced energy-efficiency technologies, such as super insulation, low-E glass for windows, distributed combined heat and power, better natural ventilation, daylighting, and efficient appliances and lights. Attractive opportunities are presented by the ability to produce a portion of required hot water, air conditioning, and electricity using solar thermal and PV devices that are integrated into the building structure itself.

Although progress continues to be made to lower manufacturing costs and increase collector performance, the relatively high capital costs of solar thermal and PV systems will continue to require incentives to encourage their widespread application. These incentives can reflect national or state initiatives (e.g., the Million

Solar Roofs initiative, the Energy Star efficiency labeling program, or LEED green buildings classifications in the US, or the Massachusetts Renewable Energy Trust's Green Schools program). Or, they may be a result of a restructuring of state or local building codes requiring higher performance. Europe, Japan, and now China and Taiwan are using policy and economic initiatives to continue growth in solar technologies.

In addition to these more distributed, building-integrated applications, the use of concentrating solar energy to produce both dispatchable and distributed electric power with power towers, parabolic troughs, and dish-engine CSP technologies has some attractive features that could lead to deployment in many countries or regions that have a high-grade direct solar resource within their boundaries. By avoiding the use of fossil fuels for electric power generation and utilizing an indigenous energy source, CSP systems increase the diversity and security of the electric supply sector. Capital costs have been lowered to the point where, with modest incentives, CSP methods could be used to provide a renewable, carbon-free source of electric power at breakeven prices of 10¢/kW$_e$h or less on a scale large enough to make a difference. For example, with a major population shift in the US to the Southwest, electric demand is increasing exactly where there is a high-grade resource for CSP. Advocates suggest that over 20,000 MW$_e$ of CSP capacity could be deployed in the US Southwest within a decade if needed. In addition, CSP is increasingly being used in hybrid systems to improve the efficiency of conventional power plants that burn coal or natural gas, in geothermal plants, and in a variety of industrial applications where thermal energy provided by CSP can displace fossil or fossil-derived energy.

Further R&D support for both PV and CSP technologies will have an impact on increasing reliability and durability while lowering module manufacturing costs (DOE, 2005). To achieve these objectives, the standardization of components needs to be improved, as do the testing of components and complete systems, in order to increase both product quality and consumer confidence. The National Center for Photovoltaics and SunLab's testing facilities are good examples of such assets to carry out these important functions for the US. International activities outside the US are moving rapidly, spurred by economic policies, and are providing many valuable lessons in the deployment of solar technologies through global organizations such as SolarPACES.

Problems

13.1 Estimate how much collector area and storage capacity would be required for an active solar hot-water system designed to supply the total needs for two four-person families, one living in Manchester, New Hampshire, where the latitude is 44+°N, and the other in Albuquerque, New Mexico, at 35+°N. The heat capacity of water is about 4,200 J/kg°C, and the hot-water supply temperature in both houses is 75°C (140°F). State and justify all additional assumptions made.

13.2 If we wanted to supply all the electricity needs for New York City (NYC), with a population of about 10 million people, using photovoltaics technology, how much land area would we need? What other elements would be required for such an idea to work for NYC? How large of an investment would this involve, and how would the price of electricity in ¢ per kW$_e$h have to increase in order to recover that investment in 10 years at an interest rate of 8%? For comparison, the average New Yorker paid 12¢/kW$_e$h in 2002.

13.3 Estimate the amount of solar heating that is lost as a result of using one or two tempered 1/8 in thick glass plates covering a flat-plate absorber. The transmission coefficient for radiation is 2% for wavelengths greater than 3 μm and 80% for wavelengths ranging from 0.2 to 3 μm.

13.4 The amount of solar energy captured in a given application is expressed in terms of how much thermal energy is delivered relative to the total demand or load. This amount is often referred to as the production function (Q_s). Using the Kreith and Kreider (1978) method of analysis, a simplified empirical model of a solar building in Boston can be developed to relate Q_s parametrically to the load in GJ (L), the amount of storage in m^3 (S), and the collector surface area in m^2 (A_c) as:

$$Q_s = L\left[0.8 + \ln\left[\left(\frac{A_c}{L}\right)^{1/3}\left(\frac{S}{L}\right)^{1/20}\right]\right] = 100\,\text{GJ}\,.$$

If the collector area is increased by 10%, what happens to Q_s? If the amount of storage is increased by the same amount, what happens to Q_s? What do you conclude from this comparison?

13.5 CSP for cooking! Let's suppose that you want to cook 1 lb of hot dogs using a parabolic trough concentrator on a clear June day in Los Angeles. The hot dogs would be skewered on a stiff piece of wire and aligned along the axis of the trough in the same position in which the absorber/receiver normally would be placed. The desired cooking time is 10 min, with the resulting surface temperature of the hot dog about 450°F. How would you design the reflector surface? Specifically, what would be the length and width of the parabolic cylinder?

13.6 Estimate how much hot water you would use for your personal needs for one week during a typical winter school break. If you wanted to use solar energy to provide the hot water, estimate what surface area of flat-plate collectors would be required if you were located in Denver.

13.7 What are the incremental savings that result from increasing the efficiency of a PV collector by 1% in terms of collector area and costs? Assume that the PV module represents about 50% of the total PV system cost.

13.8 Let's assume a world of 10 billion people with an average demand for electricity of 1 kW_e per person (720 kW_eh/month) for providing lighting and for running refrigerators, other appliances, TVs, computers, etc. What surface area of polycrystalline silicon PV collectors would be required to provide the electrical needs for 10 billion people? How much electrical storage capacity do you estimate would be needed? If lead acid batteries were used to store the energy, what mass of batteries would be required? (Hint: see chapter 17, table 17.1.)

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