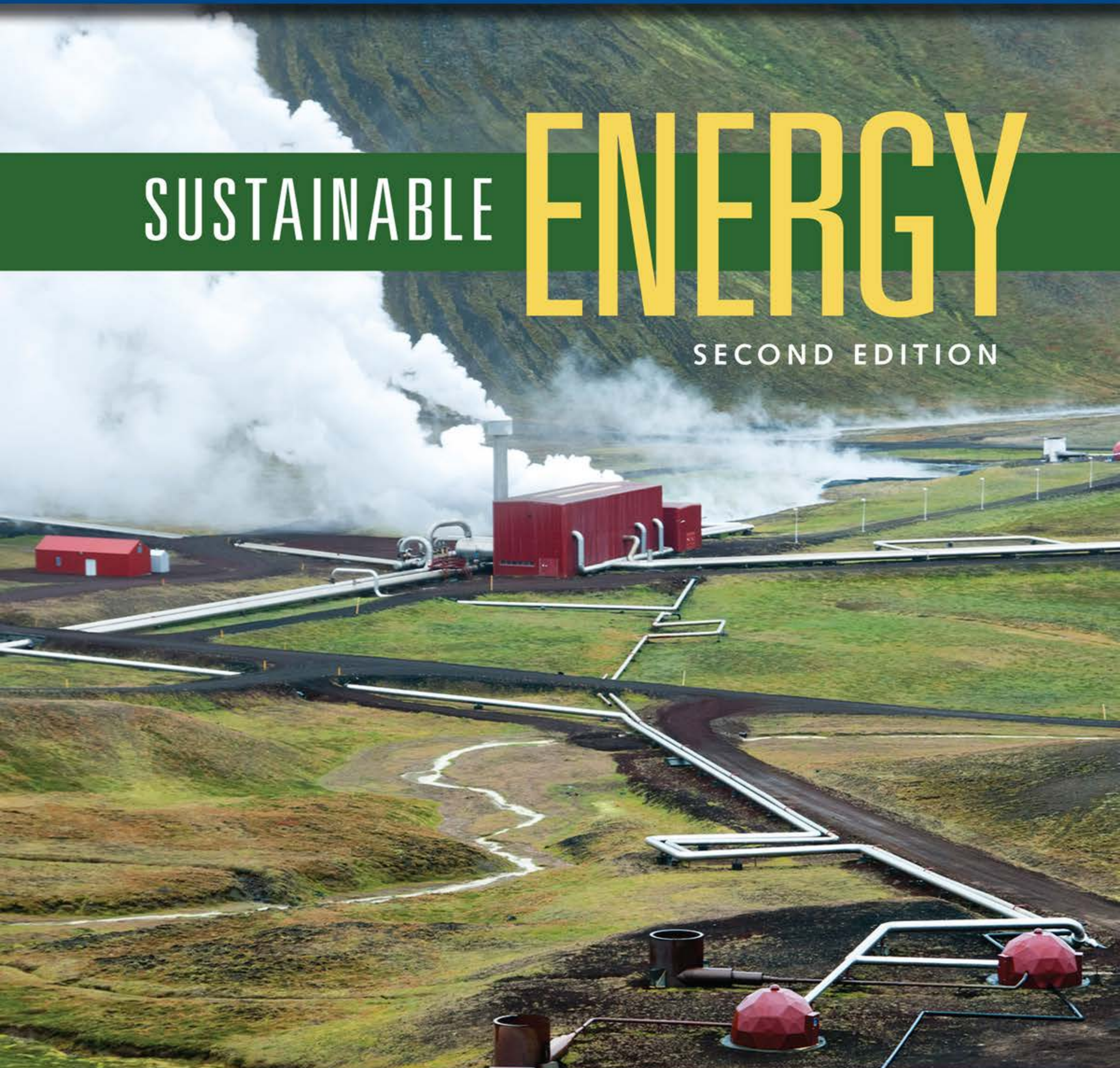
SI EDITION

SUSTAINABLE ENERGY

SECOND EDITION



RICHARD A. DUNLAP

PART IV

Renewable Energy

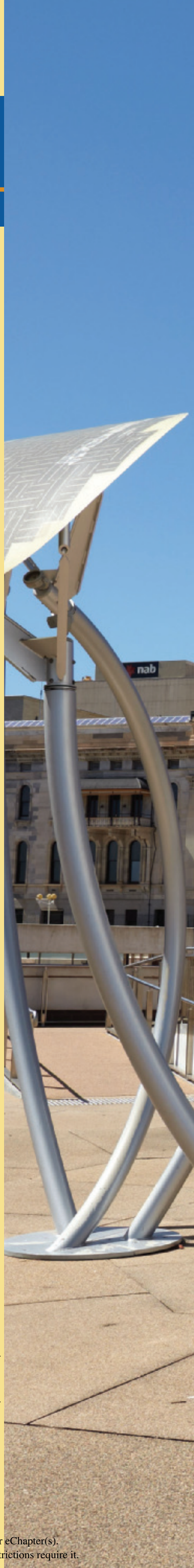
There is a clear need to look beyond fossil fuels and nuclear energy for the future. A number of possible viable alternative energy sources are available or are being researched. It is essential to carefully consider the pros and cons of each of these energy technologies. It is not always obvious how much they improve on fossil fuels because of the complexity of fully assessing the environmental impact of infrastructure development and operation and the difficulty of evaluating the economic aspects of particular energy generating methods.

We cannot create energy. Energy production methods are sometimes referred to as energy harvesting technologies because they merely convert primary energy sources from nature (e.g., solar energy, wind, geothermal, etc.) into other forms of energy that we can readily use (e.g., electricity, heat, biofuels, etc.). A major obstacle in the implementation of renewable energy technologies, compared with fossil fuels and nuclear, comes from the low energy density of alternative energy resources. This means in many cases that extensive infrastructure is necessary (e.g., in the case of solar photovoltaics) to match the generating capacity of even modest fossil fuel–fired facilities. Any technology that converts primary energy into usable energy involves a large number of factors that contribute to its environmental and economic desirability. A systematic approach to the assessment of any potential alternative energy technology is to consider how well it fits the CURVE (clean, unlimited, renewable, versatile, and economical). An evaluation of each of these factors provides an objective criterion for determining the viability of certain approaches:

- *Clean*: The environmental impact of an energy source is a crucial factor for its evaluation. A detailed life cycle assessment is beneficial in establishing whether the technology is, in fact, cleaner than fossil fuels.
- *Unlimited*: Of course, no energy source is truly unlimited, but the available quantity of some, like solar energy, is much greater than the total energy use of humankind. The greater the availability, the larger the contribution a resource can make to our future energy needs.
- *Renewable*: Some resources are available in large quantities but do not have an infinite lifetime. This is true, for example, of fossil fuels, which fulfill nearly all our energy needs but will not last indefinitely. They are clearly not renewable. Other resources, such as wave and tidal energy, are renewable but limited in their availability.
- *Versatile*: We use different types of energy for different purposes (e.g., thermal energy for heating buildings or electricity for operating appliances). Of course, one type of energy can be converted into another, but there are always conversion losses, and sometimes the losses can be very large. Although no type of energy can satisfy all our needs, those that have high energy density and are portable fulfill the most demanding applications, such as transportation.
- *Economical*: Any new energy technology must compete with existing technologies, particularly those that are well-established, reliable, and economical. This means that fossil fuels are the first point of reference in determining economics. Technologies like solar photovoltaics face a serious challenge because they do not compete economically.

This part of the text considers the most important approaches to alternative energy and evaluates how well they fit the CURVE and how likely they are to find a place in a future fossil-fuel-free energy economy.

The solar tree in the photograph is located at the Festival Centre, Adelaide, SA, Australia, and similar trees exist in many locations worldwide. Solar trees produce electricity by means of photovoltaic (PV) panels, and this electricity can be stored in a battery system. Because of the limited PV surface area, the solar tree is not intended for large-scale energy production. It is more akin to a sculpture that merges artistic design with modern renewable energy technology and serves to promote alternative energy to the public. ■



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CHAPTER 8

Direct Use of Solar Energy

Learning Objectives: After reading the material in Chapter 8, you should understand:

- The energy content and properties of the sunlight incident on the earth.
- The mechanisms for heat transfer.
- Conductive heat transfer through materials and the use of *R*-values.
- Radiative heat transfer from surfaces.
- The design and operation of a thermal solar collector.
- The energy requirements for residential space heating.
- The description of heating needs on the basis of degree days.
- The storage of thermal energy and the heat capacity of solids.
- The use of passive solar heating techniques as a component of residential heating needs.

8.1 Introduction

Solar radiation is a virtually unlimited source of renewable energy. The simplest technology that makes use of solar energy takes advantage of the heat produced when a material absorbs electromagnetic radiation. This heat may be used directly for space heating or hot water production in residential or office buildings, or it may be stored for use during overcast days or at night. Systems that make use of solar energy for this purpose may be active or passive. *Active systems* use electricity to circulate a fluid, such as water, that absorbs energy from solar radiation and is then used to distribute that energy in the form of heat where it is needed in a building. *Passive systems* merely use the thermal properties of the natural components of a building's structure for the absorption, storage, and distribution of heat in the building.

To understand how solar energy can be utilized, it is first necessary to have knowledge of some of the properties of sunlight, and this chapter begins with a review of the characteristics of solar radiation. It is also necessary to understand the thermal properties of materials to appreciate how solar radiation is absorbed by various materials and converted into thermal energy. This chapter therefore also overviews the thermodynamic properties of the construction materials used in active and passive solar heating systems, as well as those that are appropriate for the storage of thermal energy.

Adrian Lyon/Alamy Stock Photo

8.2 Properties of Sunlight

The total power output from the sun (as given in Chapter 7) is 3.8×10^{26} W and is emitted isotropically. At the distance of the earth's orbit, this power has a density given by the total power divided by the surface area of a sphere with a radius equal to the average distance between the sun and the earth (1.49×10^{11} m, defined to be one astronomical unit). Minor fluctuations occur during the year because the earth's orbit is an ellipse, not a circle, but these variations are negligible for the present discussion. (Actually, the earth is closer to the sun by about 3% when it is winter in the northern hemisphere.) Thus, the tilt of the earth's axis gives us seasons, not variations in the distance between the earth and the sun. The power density per unit area is therefore given as

$$\frac{P}{A} = \frac{3.8 \times 10^{26}\text{W}}{4\pi \times (1.49 \times 10^{11}\text{ m})^2} = 1367\text{ W/m}^2. \tag{8.1}$$

This value of the power per unit area is referred to as the *solar constant* and has been measured using sensors on satellites outside the earth's atmosphere. The solar spectrum is very closely approximated by the radiation from a black body at 6000 K. This power spectrum is shown in Figure 8.1. The *irradiance*, as shown in the figure, is the power per unit area per unit wavelength. The total power per unit area at all wavelengths is given by the integrated area under the curve in the figure. The portion of the spectrum in the visible part of the electromagnetic spectrum is indicated. The small anomalies that occur in addition to the smooth curve expected for black body radiation are due to atomic processes that occur in the gas in the outer portions of the sun's atmosphere.

The total solar power incident on the earth is given by the power density times the apparent area of the earth. To the incident solar radiation, the earth appears as a disk with an area πr^2, where r is the earth's radius (6.731×10^6 m), so

$$P_{\text{total}} = (1367\text{ W/m}^2) \times 3.14 \times (6.371 \times 10^6\text{m})^2 = 1.73 \times 10^{17}\text{ W}. \tag{8.2}$$

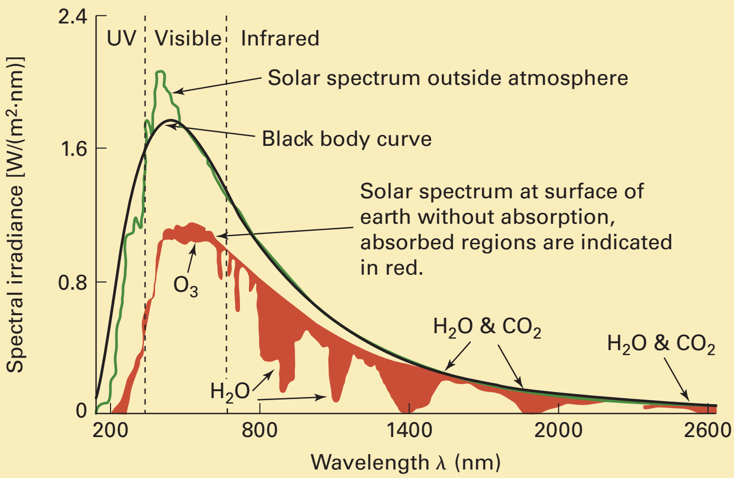


Figure 8.1: The solar spectrum.

Based on G. Li et al. "Recent Progress in Modeling, Simulation, and Optimization of Polymer Solar Cells," Photovoltaics, an IEEE Journal, 2 (2012) 320–340 AND http://www.itacanet.org/the-sun-as-a-source-of-energy/part-2-solar-energy-reaching-the-earths-surface/

Much of the radiation that arrives at the outside of the earth's atmosphere is either reflected back into space or absorbed by the atmosphere. Actually only about half of the total incident sunlight reaches the surface of the earth. The power spectrum of the solar insolation at the earth's surface compared with the spectrum of sunlight outside the earth's atmosphere is shown in Figure 8.1. The characteristic features in the spectrum are caused by absorption at certain wavelengths by various atoms and molecules in the atmosphere. The power per unit area that arrives at the surface of the earth, integrated over all wavelengths, is referred to as the *insolation*. The average insolation at the earth's surface is given by the total power in equation (8.2) times the fraction transmitted through the atmosphere and divided by the total surface area of the earth ($4\pi r^2$):

$$\frac{P}{A} = \frac{0.5 \times 1.73 \times 10^{17}\,\mathrm{W}}{4\pi \times (6.371 \times 10^6\ \mathrm{m})^2} = 168\ \mathrm{W/m^2}. \tag{8.3}$$

This is the solar insolation on a horizontal surface averaged over the entire surface and averaged over all time (day and night). The average integrated daily insolation is a measure of total incident energy per unit area for an entire day and is expressed as ($168\ \mathrm{W/m^2}$) $\times$ (86,400 s/d) = $14.5\ \mathrm{MJ/m^2}$ (Section 8.5).

The insolation at any given location on earth at any given time depends on several factors. The factors that can be readily predicted are

- The time of day.
- The day of the year.
- The latitude.

An additional condition that is difficult to predict exactly is the weather. On average, the insolation at a particular location can be determined on the basis of the average typical weather conditions. For the United States, the insolation at different locations averaged over 24 hours per day for the entire year is shown in Figure 8.2. Although this figure shows the general geographical trends for the average insolation, there can be substantial local variations.

The energy of solar radiation can be used in two ways to help satisfy our energy needs: direct use for heating or for the production of electricity. The former use is considered in the present chapter, and the latter is discussed in Chapter 9.

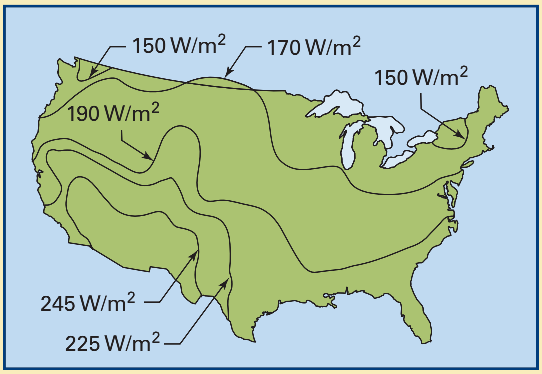


Figure 8.2: Yearly 24-hour averages of insolation on a horizontal surface for the United States.

U.S. Department of Energy

8.3 Heat Transfer

To consider the details of the design of solar collectors, it is necessary to consider how thermal energy is transported. Heat may be transported by conduction, convection, or radiation.

8.3a Conduction

According to the second law of thermodynamics, heat flows from hot to cold, and this basic principle allows us to quantify heat transport by conduction through materials. If a temperature difference exists across a piece of material, then the rate at which energy is transported from the hot side to the cold side (i.e., the power) is:

- Proportional to the magnitude of the temperature difference ($T_h - T_c$).
- Proportional to the cross-sectional area of the material (A).
- Proportional to the thermal conductivity of the material (k).
- Inversely proportional to the thickness of the material (l).

This relation is expressed mathematically as

$$P = \frac{kA(T_h - T_c)}{l}. \quad (8.4)$$

The power is expressed in W, and the thermal conductivity is in (W · cm)/(m^2 · °C) when the area is expressed in square meters (m^2), the thickness is expressed in centimeters (cm), and the temperature is in degrees Celsius (°C). For these calculations, it is reasonable to express the temperature in Celsius rather than in degrees measured on an absolute temperature scale (Kelvin) because it is temperature differences and not absolute temperatures that appear in equation (8.4). The thermal conductivities of some common materials (particularly those used in building construction) are given in Table 8.1.

Table 8.1: Thermal conductivities in (W·cm)/(m^2·°C) for some common materials.

material	k [(W·cm)/(m^2·°C)]
aluminum	20,100
iron	4600
concrete	170
brick	71
water	60
glass	59
wood (cross grain)	13
sawdust	5.9
cork	4.2
fiberglass insulation	3.8
polystyrene foam	2.84
air	2.3

To quantify the ability of a piece of material to conduct heat (or more precisely, its ability to provide insulation), it is convenient to define the *R-value* of a material, which is its resistance to heat flow. The *R*-value is determined from the thermal conductivity, as given in Table 8.1, and the thickness of the material; it is defined as $R = l/k$, so that the heat flow per unit area, as obtained from equation (8.4), may be rewritten as

$$\frac{P}{A} = \frac{T_h - T_c}{R}. \tag{8.5}$$

The *R*-value has units of $(m^2 \cdot °C)/W$, sometimes expressed as $(m^2 \cdot K)/W$ or $(m^2 \cdot s \cdot K)/J$. The *R*-value takes into account the thickness of the material, so if a 2-cm-thick piece of material has an *R*-value of, say, $R = 2$, then a 4-cm-thick piece of the same material will have an *R*-value of $R = 4$. (This simple approach deals only with conductive heat losses and is not exact if the radiative losses, to be discussed, are included.) As with resistors in an electric circuit, if several materials are placed one after the other (i.e., as resistors in a series circuit), then the *R*-values are additive:

$$R_{total} = R_1 + R_2 + R_3 + R_4 + \ldots. \tag{8.6}$$

Example 8.1

Calculate the power transferred through a piece of aluminum that is 5 cm by 5 cm by 15 cm long when the temperature on the hot end is 100°C and the temperature on the cold end is 20°C. This is the situation when one end of the bar is in contact with boiling water and the other end is at room temperature.

Solution

From equation (8.4)

$$P = \frac{kA(T_h - T_c)}{l},$$

where the following values are used to calculate the power:

$$k = 20{,}100\ (W \cdot cm)/(m^2 \cdot °C)\ \text{(from Table 8.1)}.$$

$$A = 5\ cm \times 5\ cm = 0.0025\ m^2.$$

$$T_h = 100°C.$$

$$T_c = 20°C.$$

$$l = 15\ cm.$$

Note that the area of the thermal conductor is given in m^2, whereas the length is given in cm, which, when combined with the value of k, yields power in watts. Why this approach to units is convenient will become apparent when heat transfer through building walls and windows is considered. Thus the power is calculated to be

$$P = 20{,}100 \frac{W \cdot cm}{m^2 \cdot °C} \times (0.0025\ m^2) \times \frac{100°C - 20°C}{15\ cm} = 268\ W.$$

Example 8.2

Compare the power transferred per unit area through 1 cm thick pieces of iron and glass when the temperature is 20 °C on one side and −10 °C on the other.

Solution

From equation (8.4)

$$P/A = k(T_h - T_c)/l$$

where the following values are used for both materials:

$$(T_\mathrm{h} - T_c) = (20\ ^\circ\mathrm{C} - (-10\ ^\circ\mathrm{C})) = 30\ ^\circ\mathrm{C}.$$

$$l = 1\ \mathrm{cm}$$

For iron $k = 4600$ [(W·cm)/(m^2·°C)] and for glass $k = 59$ [(W·cm)/(m^2·°C)]. Thus, for iron the power transferred will be

$$P/A = (4600\ [(\mathrm{W\cdot cm})/(\mathrm{m}^2\cdot{}^\circ\mathrm{C})])(30\ ^\circ\mathrm{C})/(1\ \mathrm{cm}) = 138\ \mathrm{kW/m}^2$$

and for glass

$$P/A = (59\ [(\mathrm{W\cdot cm})/(\mathrm{m}^2\cdot{}^\circ\mathrm{C})])(30\ ^\circ\mathrm{C})/(1\ \mathrm{cm}) = 1.77\ \mathrm{kW/m}^2.$$

The iron transfers (138 kW/m^2)/(1.77 kW/m^2) = 78 times as much power. This ratio can easily be seen from just the ratios of the thermal conductivities (4600 [(W·cm)/(m^2·°C)])/(59 [(W·cm)/(m^2·°C)]) = 78

Example 8.3

Calculate the effective *R*-value for a wall comprised of an outer layer of 10 cm of brick, a middle layer of 15 cm of fiberglass insulation, and an inner layer of 2 cm of wood.

Solution

The *R*-values can be calculated for each of the layers from the values of *k* in Table 8.1:

$$\text{Brick: } R = \frac{10\ \mathrm{cm}}{71(\mathrm{W\cdot cm})/(\mathrm{m}^2\cdot{}^\circ\mathrm{C})} = 0.14\ \mathrm{m}^2\cdot{}^\circ\mathrm{C/W}.$$

$$\text{Fiberglass: } R = \frac{15\ \mathrm{cm}}{3.8(\mathrm{W\cdot cm})/(\mathrm{m}^2\cdot{}^\circ\mathrm{C})} = 3.95\ \mathrm{m}^2\cdot{}^\circ\mathrm{C/W}.$$

$$\text{Wood: } R = \frac{2\ \mathrm{cm}}{13(\mathrm{W\cdot cm})/(\mathrm{m}^2\cdot{}^\circ\mathrm{C})} = 0.15\ \mathrm{m}^2\cdot{}^\circ\mathrm{C/W}.$$

The total *R*-value for the wall is $R = (0.14 + 3.95 + 0.15)$ m^2·°C/W = 4.24 m^2·°C/W. This can then be used to calculate the energy transferred per unit time per unit area through the wall. Clearly, in this example, the insulating properties of the wall come almost exclusively from the presence of the fiberglass insulation.

Consider a calculation for a piece of window glass. Standard window glass is about 0.3 cm thick, and, using the thermal conductivity for glass given in Table 8.1, one calculates $R = 0.005$. Thus a single pane of window glass provides virtually no insulation on its own. The principal reason that a window reduces conductive heat transfer is that it prevents air flow. A layer of stationary air is created near the surfaces of a pane of glass, and the insulating properties of this nonmoving air are of relevance. When the R-value of this air layer is taken into account, the effective R-value for the pane of glass is about $R = 0.18$. The window also eliminates convective heat transfer from the inside of the building to the outside by preventing air from actually flowing from the inside to the outside. Figure 8.3 illustrates the relationship of

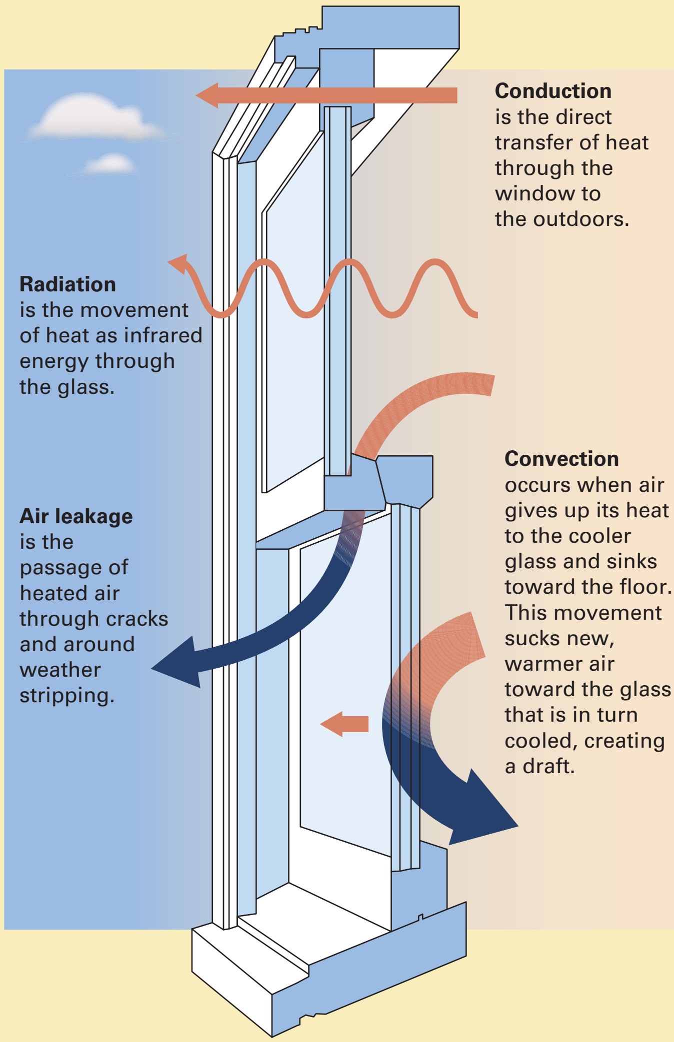


Figure 8.3: Illustration of heat losses through a window.

Based on http://www.finehomebuilding.com/CMS/uploadedImages/Images/Homebuilding/Articles/h00029_02_lg.gif; http://www.greenspec.co.uk/windows.php different heat loss mechanisms through a window, including conduction (as discussed), convection, and radiation.

8.3b Convection

Convection is an important component in the transfer of heat and is certainly illustrated by the insulating effects of the dead air layer near a pane of glass, as just explained. Convection causes heat transfer by the movement of a fluid. The physics of this process depends on the properties of the fluid, such as density and viscosity. A quantitative description of convection is very complex and is not considered in this text.

8.3c Radiation

All objects that are at a temperature above absolute zero radiate energy. The total power per unit surface area radiated by a black body at a temperature T is given by the Stefan-Boltzmann law as

$$\frac{P}{A} = \sigma T^4, \tag{8.7}$$

where σ is the Stefan-Boltzmann constant 5.67×10^{-8} W·m^{-2}·K^{-4}. Because this expression deals with the absolute temperature of the object (not a temperature difference), it is essential to represent the temperature in Kelvin. This expression shows that the total amount of radiation produced by a black body is a sensitive function of its temperature. In general, objects are not perfect black bodies and therefore do not radiate as much energy as a black body at the same temperature would. The ratio of the energy radiated by a body to that radiated by a black body at the same temperature is called the *emissivity*, ε. Thus equation (8.7) can be written for a real object as

$$\frac{P}{A} = \varepsilon\sigma T^4, \tag{8.8}$$

where ε can have values from 0 to 1 and is a measure of how effective the surface of a particular material is at radiating energy. The emissivity can vary considerably for different materials, and for a particular material it can vary to some extent as a function of temperature. Most common building materials like glass, wood, steel, most painted surfaces, and so on have emissivities of about 0.9 at around room temperature.

In addition to the temperature dependence of the total energy produced by a surface, the wavelength of the radiation produced is also a function of the temperature. The distribution of wavelengths produced by the sun was shown in Figure 8.1. For surfaces at lower temperatures than the sun, the black body spectrum is shown in Figure 8.4 on the next page. Clearly, as the temperature decreases, the total radiated power decreases (as evidenced by the area under the curves in the figure), and the wavelength of the maximum in the spectrum increases. For the sun (a black body at about 6000 K), the peak is in the visible portion of the spectrum. For a surface at, say, 350 K (or about 75°C), the peak is well into the infrared portion of the spectrum.

In addition to emitting radiation, all surfaces absorb radiation that is incident on them. The ability of a surface to absorb energy is its *absorptance, a*, and generally surfaces that are good at emitting radiation are also good at absorbing it. A surface that has a given value of the emissivity, ε, at a certain temperature has an absorptance that is equal to the emissivity, $a = \varepsilon$, for radiation with a wavelength that is characteristic of that temperature.

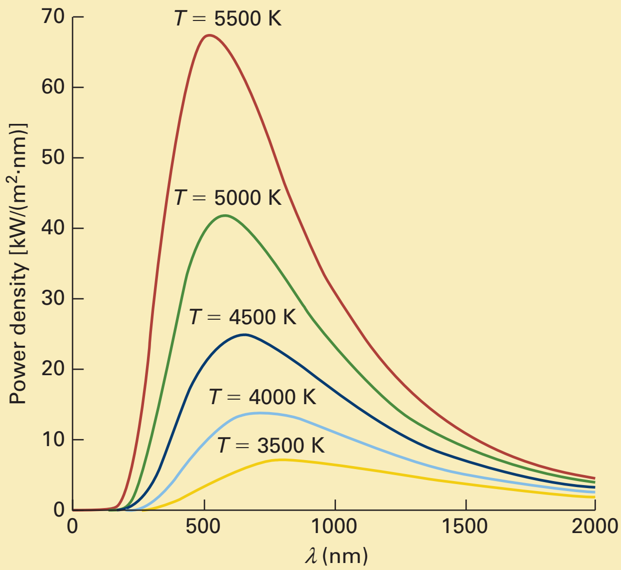


Figure 8.4: Wavelength dependence of black body radiation for surfaces at different temperatures. The vertical axis gives the power radiated per unit area per unit wavelength.

Based on Encyclopaedia Britannica, Wien's law, http://www.britannica.com/EBchecked/topic/643338/Wiens-law

Example 8.4

Calculate the power emitted by 1 m^2 of the surface of the sun.

Solution

From equation (8.8),

$$\frac{P}{A} = \varepsilon\sigma T^4 \qquad \text{or} \qquad P = A\varepsilon\sigma T^4,$$

where the following values are used:

$A = 1\ \text{m}^2$.

$\varepsilon = 1$ (because the sun behaves as a black body).

$\sigma = 5.67051 \times 10^{-8}\ \text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}$ (from Appendix II).

$T = 6000$ K (from the text).

This gives

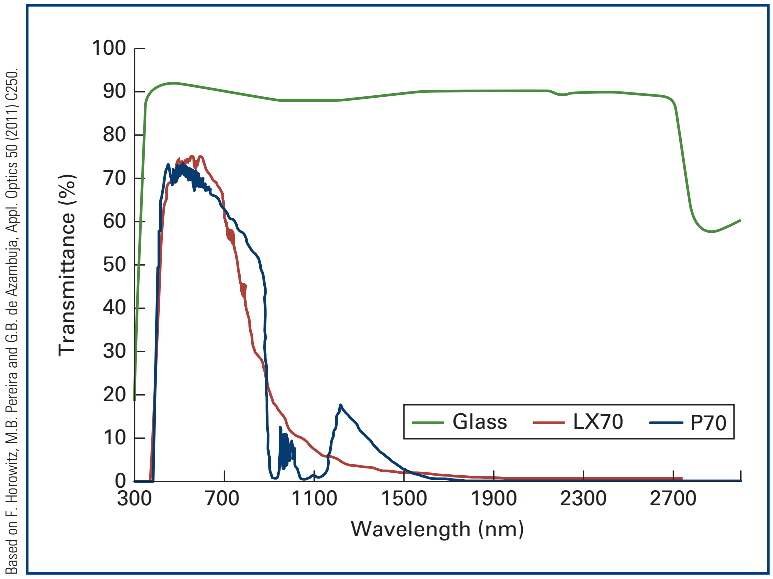
$$P = (1\ \text{m}^2) \times 1 \times (5.67051 \times 10^{-8}\ \text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-4}) \times (6000\ \text{K})^4 = 73.5\ \text{MW}.$$

ENERGY EXTRA 8.1

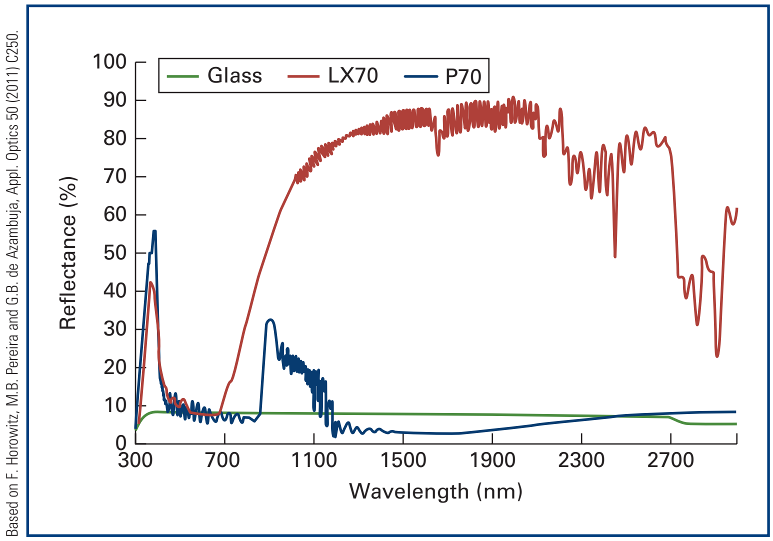
Optical coatings

Passive solar heating relies on the optical properties of windows. It is generally desirable that windows are as transparent as possible in the visible portion of the electromagnetic spectrum. The natural high transmission in the visible and low transmission in the infrared portions of the spectrum exhibited by window glass give rise to passive solar heating inside a building. However, engineering materials with specific optical properties allow for substantially more control of radiative heat flow through windows at the various wavelengths. The transmittance as a function of wavelength is shown in the figure to the right for plain glass and for glass that has been coated with two different materials, a polymer-based coating and a metal-dielectric coating. Over the visible portion of the spectrum (about 350–650 nm), both coated materials are fairly transparent, transmitting about 70% (compared to 90% for plain glass) of the incident radiation. Although glass only begins to become nontransparent well into the infrared (above 2700 nm), the coated glass becomes nontransparent in the very near infrared, thus blocking a much larger portion of long wavelength re-emitted radiation (see Chapter 4 on the greenhouse effect).

The reflectance of the coated and uncoated glass is shown in the figure to the right. Here the behaviors of the two coated materials are seen to be very different. The polymer-coated glass is fairly similar to glass, while the metal-dielectric–coated glass becomes very reflective in the infrared. These materials may be utilized to optimize passive solar heating in the winter.



The transmittance of glass and glass coated with a polymer coating (P70) and a metal-dielectric layer (LX70).



Reflectance of glass and glass coated with a polymer coating (P70) and a metal-dielectric layer (LX70).

Continued on page 270

Energy Extra 8.1 continued

As illustrated in the figure, the transmittance of the coated glass allows light to enter but minimizes long-wavelength radiation heat loss back through it.

Topic for Discussion

Solar blinds can make an important addition to high-efficiency windows. These are like venetian blinds with one side coated with a reflective material and the other side coated with an absorptive material. The blades can be oriented with the reflective side out and the absorptive side in, or vice versa. Discuss how these might be used during the day and night and during different seasons to optimize heating efficiency in a home.

8.4 Solar Collector Design

Systems for utilizing solar radiation for heating purposes may be either active or passive. An *active system* is one in which heat produced from sunlight is transported and stored by circulating an appropriate fluid (typically water or air) using pumps or blowers. A *passive system* merely relies upon building design to utilize sunlight to heat the air or other material in the building. Active solar heating systems use either traditional flat plate collectors (Figure 8.5) or evacuated tube collectors. The operation of a flat plate collector is described in the present section. Evacuated tube collectors are discussed in Energy Extra 8.2. The basic design of the flat plate collector is shown in Figure 8.6 on the page 274. The collector is basically an insulated box with a window on the front side to allow sunlight to enter. The sunlight is absorbed by a collector plate, and the heat is transferred to water flowing through pipes attached to the plate. The properties of the collector plate are very important for the operation of the collector. Ideally, the plate should absorb as much of the solar radiation as possible and lose as little energy as possible through reirradiation. The relationship between absorptance and emissivity, as previously explained, needs to be considered carefully in the analysis of the flat plate collector. The radiation that is absorbed in the form of sunlight is produced by the sun and has a spectrum that is basically similar to 6000 K black body radiation (Figures 8.1 and 8.4) with

Figure 8.5: Flat plate solar collector installation.

Richard A. Dunlap

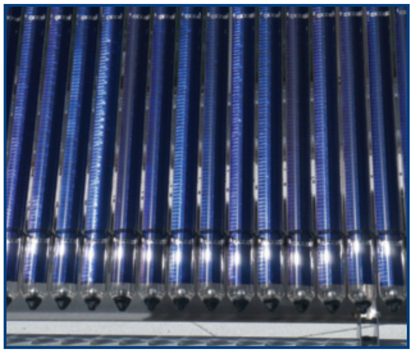
ENERGY EXTRA 8.2

Evacuated tube solar collectors

An alternative design to the traditional flat plate solar collector that has come into use in recent years is the evacuated tube solar collector. The evacuated tube solar collector consists of a series of evacuated glass tubes, each of which contains an absorber. Typically the absorber consists of a metal plate (generally painted black to absorb light) thermally connected to a tube that is closed on both ends, as shown in the figure. The tube contains a quantity of working fluid (a mixture of propylene glycol and water is commonly used) that undergoes a phase transition to the vapor state when heated. The heated vapor rises to the top of the tube, where it transfers heat to water through a heat exchanger (called a manifold). The working fluid then condenses and falls back to the bottom of the tube. The evacuated glass tube serves to reduce heat loss. The water that is heated in the manifold can be used for heating or domestic hot water.

Richard A. Dunlap

Evacuated tube solar collector.



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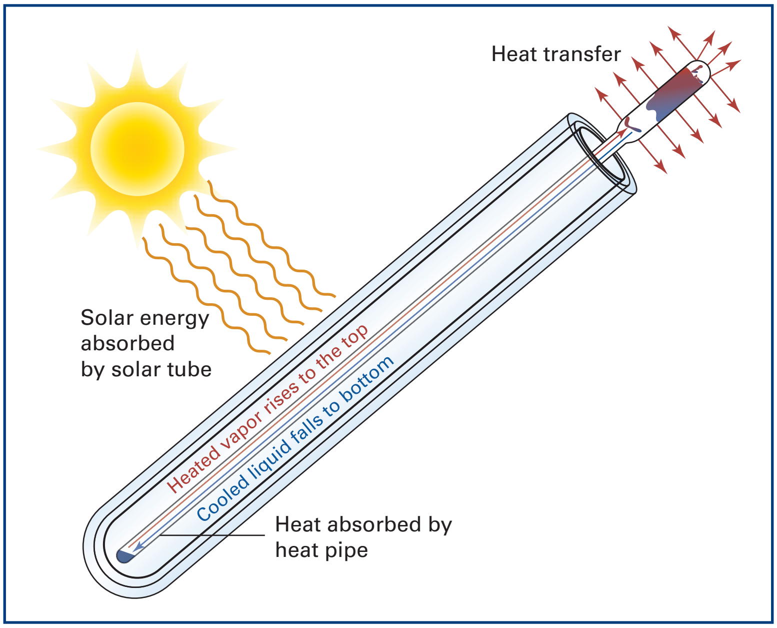
Close-up of evacuated tube solar collector.

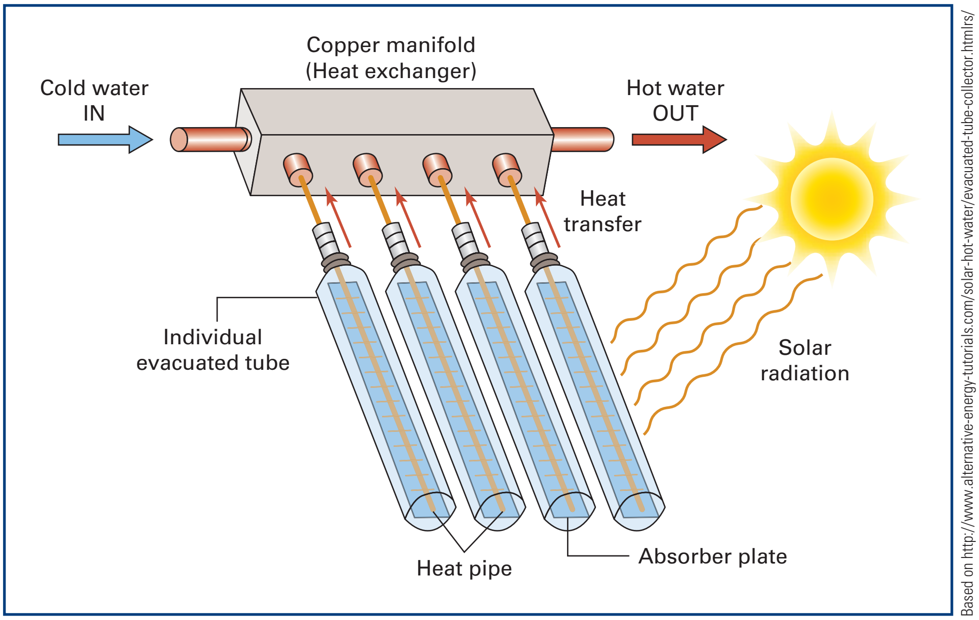


Based on http://www.solarpanelsplus.com/evacuated-tube-collectors/

Internal structure of a typical evacuated tube solar collector.

Continued on page 272

Energy Extra 8.2 continued



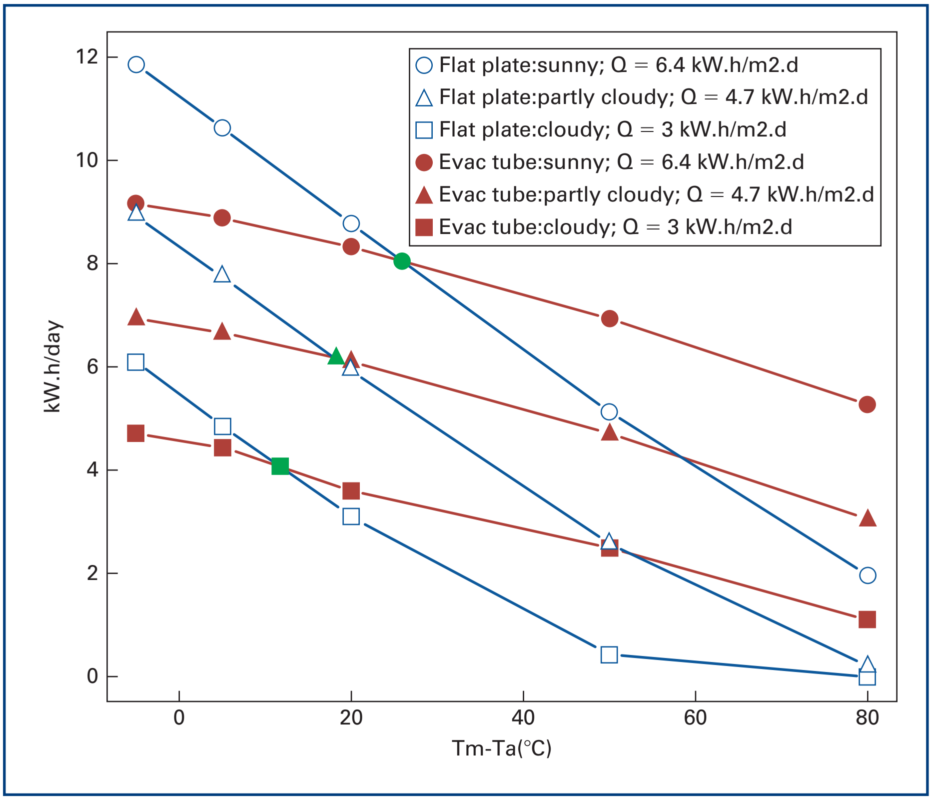
Connection of evacuated tube solar collectors to heat exchanger.

In principle, evacuated tube solar collectors can be used in the same applications as flat plate collectors, and each has advantages in certain situations. Evacuated tube collectors have the disadvantage that only about 70% of the total collector area absorbs solar radiation because of the space around the absorber in the glass tube and the spaces between the tubes. Evaporated tube collectors are a newer technology, and over time their long term reliability may be determined. They also tend to be more expensive per square meter, typically about twice the cost of a flat plate system of the same absorber area. They do have the advantage that their more modular design improves serviceability and extendibility.

A major consideration for the comparison of these two different technologies is their relative efficiencies. The graph in the figure shows the outputs of two similarly-sized collectors as a function of the difference between the manifold water temperature (T_m) and the ambient temperature (T_a). In all cases the efficiency decreases with an increasing temperature difference. This is merely a result of the greater heat loss to the environment with the greater temperature difference. However, this decrease is not as significant for the evacuated tube collector as it is for the flat plate collector. This is a direct result of the more effective insulation provided by the evacuated space in the tube. The net result of these features is that there is a crossover point where the evacuated tube collector becomes more efficient for larger temperature differences. The crossover point shifts to a higher temperature difference when there is greater insolation. While the graph shows the general features of the relationship between the efficiency of the evacuated tube collector and the flat plate collector, the details of this behavior, i.e., actual efficiencies and crossover points, depend on specific details of the collector designs.

Continued on page 273

Energy Extra 8.2 continued



Comparison of power output from flat plate and evacuated tube collectors for different insolation conditions and different temperature differences. The flat plate collector had an absorber area of 2.8 m^2, and the evacuated tube collector had an absorber area of 3.1 m^2.

Topic for Discussion

Consider the economic viability of evacuated tube collectors and flat plate collectors for domestic hot water production for a manifold temperature of 50°C. Provide a quantitative comparison for different climatic conditions, e.g., Montreal in the summer or winter and New Orleans in the summer or winter.

a peak wavelength of about 500 nm. The energy that is reirradiated by the collector plate is characteristic of the temperature of the plate (which might be at around 350 K). This reirradiated radiation is in the infrared portion of the spectrum with a peak at about 8000 nm. The ideal design for the collector plate would be to have a large absorptance at 500 nm and a small emissivity at 8000 nm, so that the collector absorbs substantial energy from sunlight but loses very little of it by reirradiation (Figure 8.7 on the next page). Specially designed collector surface coatings have a high absorptance for visible radiation and low emissivity for infrared radiation. Flat black paint is a simple alternative that works well.

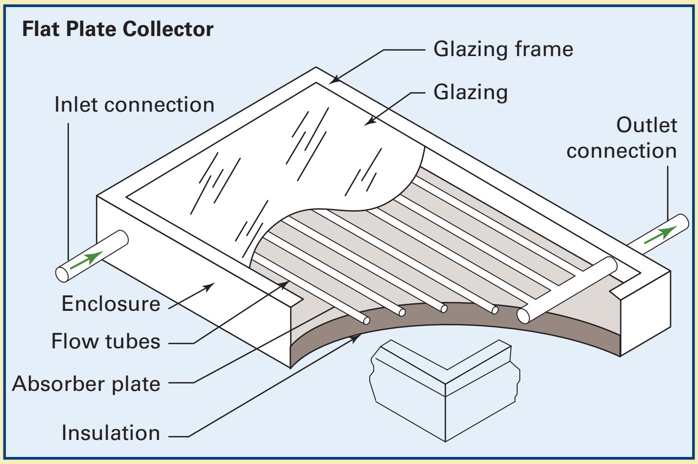


Figure 8.6: Design of a flat plate solar collector.

U.S. Department of Energy

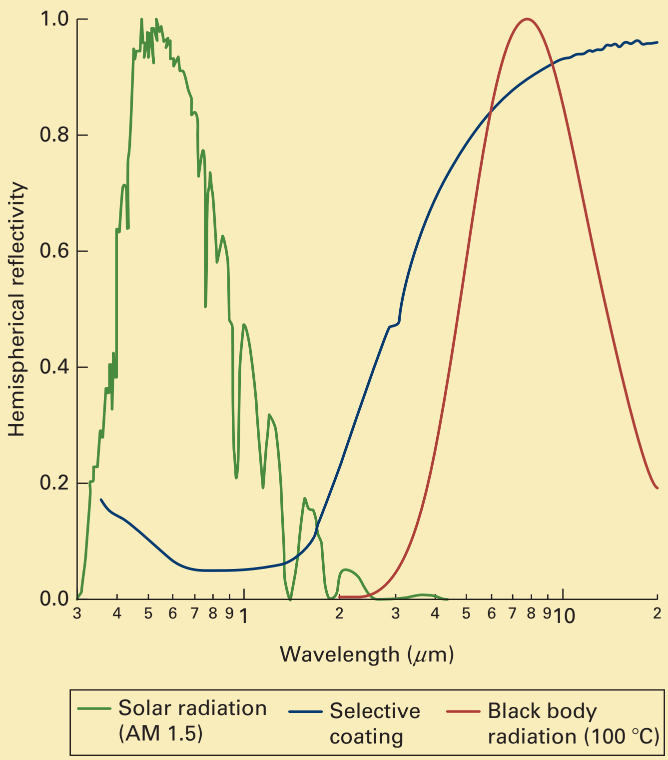


Figure 8.7: Measured reflectance of a suitable solar collector coating material relative to the solar spectrum (AM 1.5) and the black body curve at 100°C (373 K).

Based on P. Oelhafen and A. Schüller, "Nanostructured materials for solar energy conversion," Solar Energy 79 (2005) 110–121.

The glass plate on the front of the collector is also an important factor in the collector operation. Glass has a high transmittance for visible radiation but a low transmittance for infrared radiation. Thus, much of the energy that is reirradiated by the warm collector surface is not transmitted through the glass cover and is trapped inside the collector box. This is the same principle as the greenhouse effect discussed in Chapter 4 and is the reason that the interior of an automobile gets hot on a sunny day.

The efficiency of the collector is the ratio of the heat absorbed by the water to the energy incident on the collector. The loss of energy by reirradiation from the hot collector surface is one factor that limits the efficiency of the collector. Heat loss by conduction through the walls of the box is another contributing factor. Equation (8.8) for radiative heat transfer and equation (8.4) for conductive heat transfer both show that, as the temperature of the collector increases, so does heat loss. At some point, the losses equals the energy incident on the collector, and the efficiency goes to zero. Thus, from an efficiency standpoint, it is advantageous to operate the collector at lower temperatures, and the maximum efficiency occurs when the collector is at the same temperature as its ambient surroundings.

On the other hand, the amount of energy that is actually transported to a home heating system by the water heated in the collector increases with increasing temperature (Section 8.5). From this viewpoint, it would be advantageous to operate the collector at as high a temperature as possible. However, there are practical considerations for the operating temperature based on the properties of the fluid used (e.g., water). If the temperature of the water is high, then the maximum amount of thermal energy is transported through the system. However, when the temperature of the water is high, then the heat losses between the collector and the heating system inside the house are greater. The best compromise between these conflicting criteria is generally to operate the collector at an efficiency of about 50%. This results in a collector plate temperature that is somewhat less than the boiling point of the water.

8.5 Residential Heating Needs

Active solar systems are commonly used for residential space heating and for supplemental water heating. In this section, some requirements for the design of a space heating system are considered. Because solar radiation is present only during the daytime hours, it is necessary to be able to store heat energy for use during the night. Water circulating through the collector is heated and stored in a tank, which also acts as a heat exchanger to provide heat and hot water to the house.

For the design of such a system, it is important to know how much solar energy a particular collector system can produce and how much heat a particular residence needs. The average insolation on a horizontal surface at different locations in the United States shown in Figure 8.2 is not the most useful information for this analysis. First, insolation is less in the winter (because of the angle of the sun), but this is the time of the year when heating needs are the greatest. Second, a horizontal surface is not the ideal orientation for maximizing solar energy collection. Table 8.2 shows the total daily solar energy per square meter for different collector orientations. The perpendicular collector includes a system for moving the collector (during the daylight hours) so that it always remains perpendicular to the incident solar radiation. This provides the maximum amount of energy but adds

Table 8.2: Daily integrated insolation at a typical ~40°N latitude location (Allentown, Pennsylvania, latitude 40.65°N). Monthly averages over a 30-year period from 1961 to 1990 are given for flat plate collectors at various angles. *Vertical* means south facing, and *tilted* means south facing and tilted at the optimal angle. Tracking is a two-axis tracking collector that follows the sun during the day.

month	horizontal MJ/m^2	vertical MJ/m^2	tilted MJ/m^2	tracking MJ/m^2
Jan.	6.8	11.2	11.2	13.7
Feb.	9.7	13.0	14.0	16.9
Mar.	13.3	12.2	16.2	20.2
Apr.	16.9	10.8	18.0	23.0
May	19.4	9.4	18.7	25.2
Jun.	21.6	9.0	19.4	27.0
Jul.	21.2	9.4	19.4	27.0
Aug.	18.7	10.4	19.1	25.2
Sep.	15.1	11.9	17.6	21.6
Oct.	11.2	12.2	15.1	18.4
Nov.	7.2	10.1	10.8	13.0
Dec.	5.8	9.4	9.4	11.2

Based on data from National Solar Radiation Data Base of National Renewable Energy Laboratory

considerably to the cost, complexity, and presumably, reliability of the system. An alternative is to place the collector facing south (in the northern hemisphere) and at an angle from the vertical so that deviations from perpendicular incidence are minimized. A first approximation for the optimal tilt from the vertical is 90° minus the latitude. This approach can be improved by seasonal adjustments where the tilt (from the vertical) is reduced in the winter months and increased in the summer months. Another option is to position the collector vertically and facing south. The final option is to place the collector horizontally. The table shows the daily insolation for each of these cases.

The relative insolation for the different orientations is compared with the ideal perpendicular case for January 21 (typically the coldest time of the year in the northern hemisphere) in Table 8.3. In the interest of economics and simplicity, it is preferable to have a stationary (fixed) collector. The table shows that, at the coldest time of the year, the 60° south-facing collector provides close to 90% of the ideal energy

Table 8.3: Relative insolation compared to a perpendicular collector for different orientations on January 21 at 40°N latitude.

orientation	% of perpendicular
60° south	89
vertical south	79
horizontal	43

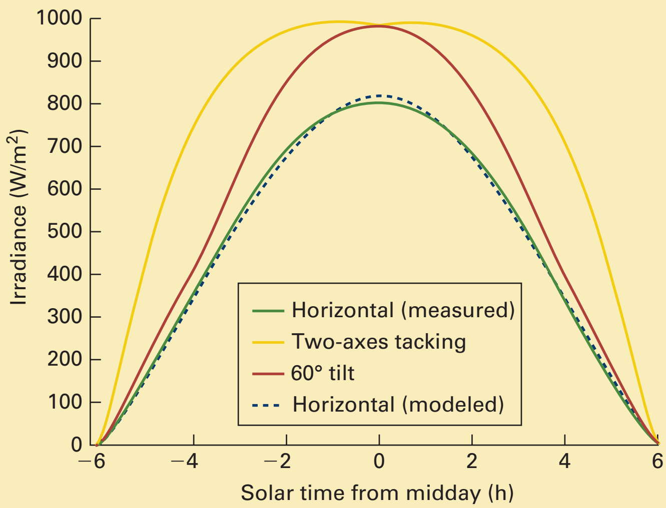


Figure 8.8: Power per unit area incident on a solar collector for different orientations.

Based on F. Cruz-Peragón, P.J. Casanova-Peláez, F.A. Díaz, R. López-García and J.M. Palomar, "An approach to evaluate the energy advantage of two axes solar tracking systems in Spain," Applied Energy 88 (2011) 5131–5142.

and is the best simple option for system design. Clearly the horizontal orientation is not desirable. Figure 8.8 shows the variations throughout the day for different collector orientations.

This discussion, along with an anticipated collector efficiency in the range of about 50%, provides an estimate for the amount of energy that can be collected for a solar collector of a certain size. The amount of energy that a house needs to fulfill its heating needs depends on several factors: the size of the house, the details of its construction, and the local climate. The climate conditions are expressed as *degree days*. One degree day, sometimes expressed as *heating degree days*, is one day during which the average outside temperature is one degree less than the desired inside temperature. In warmer climates, *cooling degree days* are used as a measure of the energy requirements for air conditioning. In this discussion, only heating degree days are considered.

Degree days, expressed for temperatures in Celsius, that is, *degree days (°C)*, are determined on the basis of an ideal inside temperature is 18.3°C. Although this may be less than the target temperature in many buildings, contributions from internal heat sources, as will be discussed, can compensate for this difference. The numbers of degree days for individual days during the year are added together to give the total number of degree days for the year, and this sum can be used as an indication of the annual heating requirements. As an example, consider a cold winter day when the average outside temperature is −5 °C. This day would contribute [18.3°C − (−5°C)] = 23.3 °C degree days towards the annual total.

The average number of degree days per year for various locations in the United States and Canada are shown in Figures 8.9 and 8.10, respectively. More accurate values for some selected cities are given in Table 8.4.

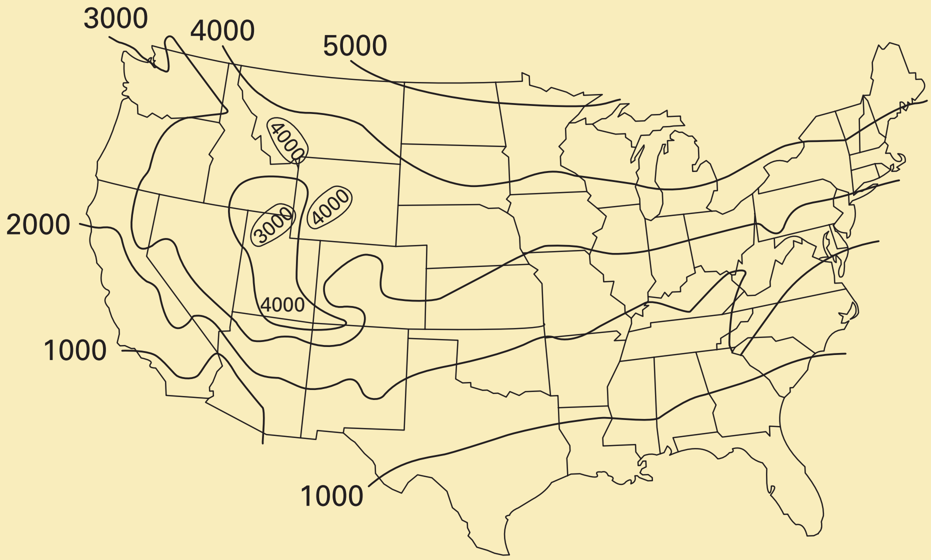


Figure 8.9: Map of the United States showing the number of heating degree days (in °C) per year (average of period 1961–1990).

National Oceanic and Atmospheric Administration (NOAA)

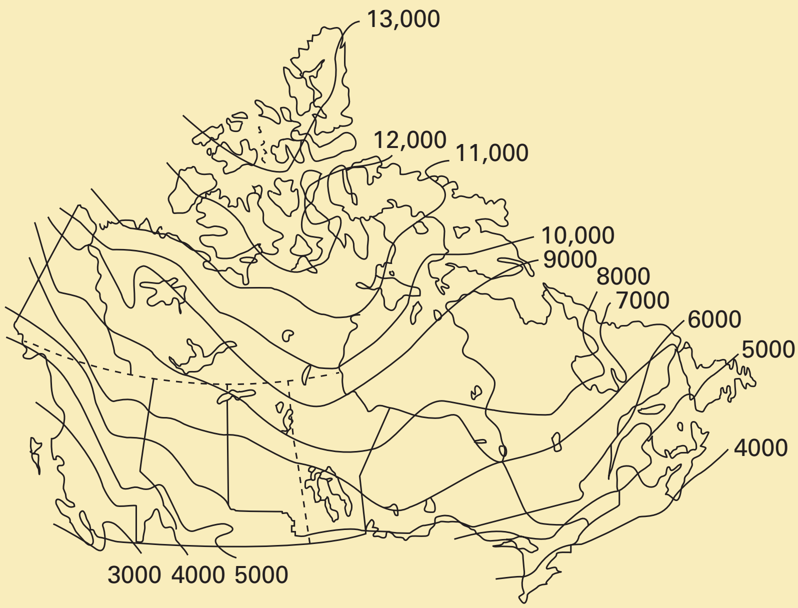


Figure 8.10: Map of Canada showing the number of heating degree days (in °C) per year.

From Hunt, Energy, Physics and the Environment, 3E. © 2007 Cengage Learning.

Table 8.4: Average number of heating degree days (in °C) per year for selected U.S. and Canadian cities. (averages for 1971–2000).

city	state/province	heating degree days per year (°C)
Honolulu	HI	0
Miami	FL	86
Phoenix	AZ	578
San Diego	CA	602
New Orleans	LA	787
San Francisco	CA	1452
Albuquerque	NM	2378
Portland	OR	2426
Baltimore	MD	2574
New York	NY	2635
St. Louis	MO	2643
Philadelphia	PA	2644
Seattle	WA	2665
Vancouver	BC	2926
Boston	MA	3128
Denver	CO	3404
Detroit	MI	3583
Chicago	IL	3607
Toronto	ON	4066
Portland	ME	4069
Halifax	NS	4367
Minneapolis	MN	4379
Montreal	QC	4575
St. John's	NL	4881
Grand Forks	ND	5281
Regina	SK	5661
Edmonton	AB	5708
Winnipeg	MB	5777
Anchorage	AK	5817
Whitehorse	YT	6811
Mt. Washington	NH	7658
Yellowknife	NT	8256
Barrow	AK	11,052
Resolute	NU	12,526

It is now necessary to relate the heat requirements for a building of a particular design to the climate as represented by the number of degree days. We could undertake a detailed calculation of heat loss through the walls, windows, roof, foundation, and so on for the building based on an analysis of the *R*-values of these various building components. However, in 1972, the United States Federal Housing Authority provided an estimate of 67 kJ/m^3 of living space per degree day (°C) for residential heating. Although construction techniques and materials have improved since 1972, this value is useful in acting as a rough guideline for heating needs: The annual heating requirements for a house are given as the volume of the house times the heat requirement per unit volume per degree day times the number of degree days per year for the location of the house.

To design a reasonable solar heating system, it is convenient to look at the daily requirements for the house in Philadelphia in Example 8.5. A winter (February) day, when the average daily temperature is, say, 0 °C, represents 18.3 degree days (°C). This will require

$$700\ m^3 \times 67\ kJ/m^3 \times 18.3 = 858\ MJ \tag{8.9}$$

of heat on that day. This may be an overestimate of the requirements for at least four reasons:

1. Passive solar heating (Section 8.6) has not been considered.
2. There is heat production within a house as a result of other activities: heat generated by people, heat from cooking, heat generated by appliances and electronics, and so on. Some typical numbers are given in Table 8.5 and can account for something of the order of 10% of the heating needs.
3. Solar heating may work in conjunction with another heating method (e.g., oil or electric) and may not be expected to fulfill all of the heating requirements (discussed further in Chapter 17).
4. Well designed contemporary buildings typically require less heat than the 1972 U.S. guideline.

For our example, it might be reasonable to aim for about 60% of the value in equation (8.9), or about 500 MJ, for a solar heating system that would contribute in a substantial way to home heating needs. From Table 8.2 (appropriate for Philadelphia), we see that a total daily insolation on the order of 14.0 MJ/m^2 can be expected for a 60° south collector. Taking into account a typical collector efficiency of 50% allows for a simple calculation of the area of the collector needed to satisfy these requirements:

$$\frac{500\ MJ}{14.0\ MJ/m^2} = 71\ m^2 \tag{8.10}$$

Table 8.5: Typical daily contributions to home heating from internal sources.

source	heat per day MJ
lights	11
cooking	7
appliances	33
electronics	5
people	12
other	5
total	**73**

Example 8.5

(a) Determine the annual heat requirements (in Btu) for a residence in Philadelphia with 250 m^2 of heated living space and 2.8-m ceilings.
(b) Estimate the annual heating costs for electric heat (at 100%) if electricity costs \$0.11 per kWh.
(c) Estimate the annual heating costs for oil heat (at 85% efficiency) if oil costs \$1.10 per liter.

Solution

(a) From Table 8.4, Philadelphia has 2644 heating degree days per year (°C), so the total heat requirement for a house with a volume of 250 $m^2 \times 2.8$ m = 700 m^3 at 67 kJ/m^3 per degree day (°C) is

$$67 \text{ kJ/m}^3 \times 700 \text{ m}^3 \times 2644 = 1.24 \times 10^{11} \text{ J}.$$

(b) The heating requirement can be converted from J to kWh (Appendix III) as

$$(1.24 \times 10^{11} \text{ J})/(3.6 \times 10^6 \text{ J/kWh}) = 34{,}445 \text{ kWh}.$$

At \$0.11 per kWh, this will cost \$3789.
(c) From Appendix V, the energy content of 1 L of crude oil (about the same as home heating oil) is 3.85×10^7 J. At 85% efficiency, this will yield about 3.27×10^7 J/L. Meeting the heating requirement of 1.24×10^{11} J will require

$$(1.24 \times 10^{11} \text{ J})/(3.27 \times 10^7 \text{ J/L}) = 3792 \text{ L of oil}.$$

At \$1.10 per L, the cost will be about 3792 L × \$1.10/L = \$4171.

A collector 7 m × 10 m would fulfill these requirements and would approximately cover the roof area of the house in this example.

Example 8.6

(a) Determine the annual heat requirements (in J) for a residence in Winnipeg with 230 m^2 of heated living space and 2.5-m ceilings.
(b) Estimate the annual heating costs for electric heat (at 100%) if electricity costs \$0.11 per kWh.
(c) Estimate the annual heating costs for oil heat (at 90% efficiency) if oil costs \$0.90 per liter.

Solution

(a) From Table 8.4, Winnipeg has 5777 heating degree days per year (°C), so the total heat requirement for a house with a volume of 230 $m^2 \times 2.5$ m = 575 m^3 at 67 kJ/m^3 is

$$67{,}000 \text{ J/m}^3 \times 575 \text{ m}^3 \times 5777 = 2.23 \times 10^{11} \text{ J}.$$

Continued on page 282

Example 8.6 continued

(b) The heating requirement can be converted from J to kilowatt-hours (Appendix III):

$$\frac{2.23 \times 10^{11}\ \text{J}}{3.6 \times 10^{6}\ \text{J/kWh}} = 6.18 \times 104\ \text{kWh}.$$

At \$0.11 per kilowatt-hour, this will cost \$6800.

(c) From Appendix IV, the energy content of 1 L of crude oil (about the same as home heating oil) is 3.85×10^7 J/L. At 90% efficiency, this will yield about 3.47×10^7 J/L. Meeting the heating requirement of 2.23×10^{11} J will require

$$\frac{2.23 \times 10^{11}\ \text{J}}{3.47 \times 10^{7}\ \text{J/L}} = 6427\ \text{L of oil.}$$

At \$0.90 per liter, this will cost \$5784.

8.6 Heat Storage

The preceding discussion provided a basis for a usable design of a residential solar heating system. However, it must be realized that the sun does not shine 24 hours a day and that the insolation value used in the previous section is a daily average. In fact, part of the problem in utilizing solar energy for heating is that in the winter, when the most heat is needed, the duration of sunshine is the least. So the energy that is collected during the day must be stored for use during the night. One may also take the approach that energy collected during sunny days can be stored to supplement heating needs during cloudy days. Heat contained in water that has been heated in a solar collector (Figure 8.6) may be stored by keeping the water in an insulated tank or transferring that heat to another material for storage. (The design of such a system is discussed further in Chapter 17; see Figure 17.16). The amount of heat that can be stored in a material is a function of the material's temperature, its mass, *m,* and its thermal properties. If a material is cooled from an initial temperature T_i to a final temperature T_f (assuming no phase transitions are involved), then the heat given up is expressed as

$$Q = Cm(T_i - T_f), \tag{8.11}$$

where C is the *specific heat* of the material. It is clear from equation (8.11) that the specific heat is a measure of the thermal energy content of a material per unit mass per unit temperature change. The *volumetric heat capacity* is defined as the heat contained in a material per unit volume per unit temperature and is obtained from the specific heat by multiplying C times the density. Table 8.6 gives the specific heat and volumetric heat capacity of some common materials. Equation (8.11) may also be written as

$$\Delta T = \frac{Q}{Cm} \tag{8.12}$$

and gives the temperature increase of a material when a quantity of heat is applied to it. From equation (8.12), it is clear that a material with a large specific heat experiences a

Table 8.6: Specific heats and volumetric heat capacities for some common materials.

material	specific heat J/(kg·°C)	density kg/m³	volumetric heat capacity kJ/(m³·°C)
water	4186	1000	4186
aluminum	895	2700	2416
iron	460	7855	3613
wood (pine)	2800	500	1400
stone (solid)	879	2560	2250
stone (loose)	879	~1500	~1300
brick	920	1800	1656
concrete	653	2300	1502
glass	837	2720	2277
sand	816	1600	1306

relatively small increase in temperature when heat is applied and that a material with a small specific heat experiences a much larger increase in temperature. Conversely, materials with large specific heats can release significant amounts of heat without undergoing large temperature changes.

Among the common materials listed in Table 8.6, water clearly has the greatest capacity for storing thermal energy, both per unit weight and per unit volume. In addition, it is convenient because it is nontoxic, relatively nonreactive, and inexpensive, and as a liquid, it provides a suitable means of transporting heat. For a space heating system that uses solar energy, it would be appropriate to store an amount of heat that is comparable to what is used daily during the winter. The following analysis provides an idea of the requirements for a useful heat storage system.

To design a system to store the 1.09 GJ calculated in Example 8.7 in a tank of water, it is necessary to know the maximum temperature of the water, T_i, and the temperature of the water after the 1.09 GJ has been extracted, T_f. The mass of water can then be obtained by rewriting equation (8.12) as

$$m = \frac{Q}{c\Delta T}. \tag{8.13}$$

Example 8.7

Calculate the amount of energy needed to heat the home in Winnipeg from Example 8.6 on a winter day when the average daily temperature is −10°C.

Solution

An average temperature of −10°C over a period of one day corresponds to [18.3°C −(−10°C)] × 1 day = 28.3 degree days (°C). For a house with a volume of 575 m^3 requiring 67 kJ/m^3 per degree day, the total energy required will be 67,000 J/m^3 × 575 m^3 × 28.3 = 1.09×10^9 J.

Example 8.8

Calculate the mass and volume of water needed to store 1.09 GJ of thermal energy if the maximum and minimum water temperatures are 65°C and 30°C, respectively.

Solution

Equation 8.13 gives

$$m = \frac{Q}{c\Delta T},$$

where $Q = 1.09 \times 10^9$ J and $\Delta T = (65°C - 30°C) = 35°C$. Table 8.6 gives $c = 4186$ kJ/(m^3·°C) for water, and, since water has a density of 10^3 kg/m^3, this is the same as 4186 J/(kg·°C). The mass of water is calculated to be

$$m = \frac{1.09 \times 10^9 \text{ J}}{(4186 \text{ J}/(\text{kg} \cdot °\text{C})) \times (35°\text{C})} = 7.4 \times 10^3 \text{ kg}.$$

This mass of water represents a volume of 7.4 m^3. This could be contained in a cubic tank about 1.9 m on a side.

Minimizing the size of the tank means maximizing T_i and minimizing T_f. The maximum temperature is limited by the temperature of the water exiting the solar collector (in order to transfer heat from the solar collector water to the storage tank water). The minimum temperature is limited by the temperature of the house (in order to transfer heat from the heating system to the room). Although an absolute maximum temperature might be 90°C and an absolute minimum temperature would be about 18°C, a reasonable range of operating temperatures that provides good efficiency for heat transfer might be between $T_i = 65°C$ and $T_f = 30°C$.

8.7 Passive Solar Heating

All buildings are heated passively by solar radiation to some extent, but the design and placement of the building can maximize these benefits. In the design of a passively heated building, the steps taken to optimize passive solar heating must not ultimately require more heat. Thus, heat gain must be balanced against heat loss. A typical home designed to optimize passive solar heating incorporates large south-facing windows (Figure 8.11). Figure 8.12 shows how building design can be used to maximize passive solar heating during the winter and minimize excess heating during the summer. A massive stone floor absorbs heat during the day (especially if it is dark colored) and reirradiates the heat during the night to distribute the effects of passive heating over a 24-hour period.

Because passive heating results from energy entering through a window and being trapped as a result of the greenhouse effect, it is necessary to consider the heat gained in comparison with the heat lost through the window. It is easiest to consider the heat lost in the context of conductive heat transfer through the window. A standard double-pane window has an *R*-value of about 0.35, and a wall without a window that

Figure 8.11: Passive solar home showing large south-facing windows.

© iStockphoto.com/EricVega

contains 15 cm of insulation will have an *R*-value of about 3.5. Thus, it is important to ensure that, on average, the energy gain through windows from passive solar heating will outweigh the energy loss resulting from the low *R*-value of the windows. The effects of the *R*-values of windows will be discussed further in Chapter 17.

The efficiency of solar energy collection under the conditions described in Example 8.9 is quite good. This calculation is based on clear sky conditions. The reduction of passive solar heating caused by clouds depends on local climate conditions. For example, if cloud cover reduces the insolation to 50% of its clear sky value, then the

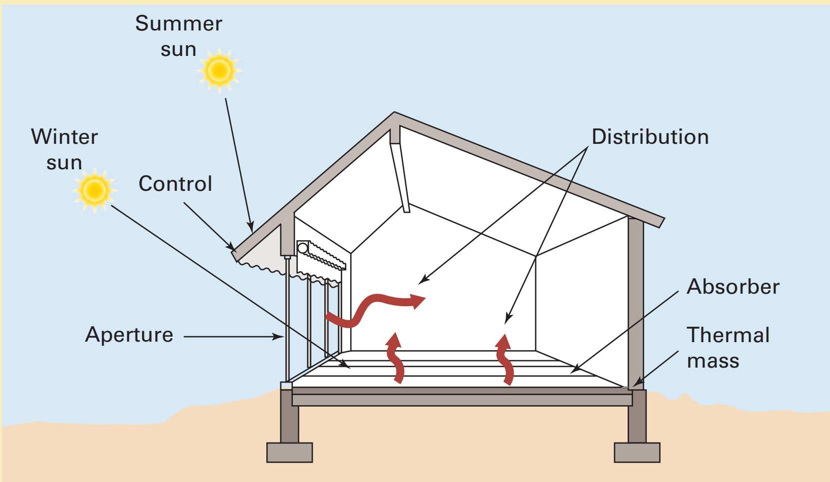


Figure 8.12: Method of utilizing solar heating during the winter and reducing solar heating during the summer.

Based on U.S. Department of Energy, http://www.energysavers.gov/your_home/designing_remodeling/index.cfm/mytopic=10270

Example 8.9

Calculate the net energy gain (per day in January) from passive solar radiation incident on a double-pane window in a house at 40°N latitude. Consider a 1.5 m × 2.5 m south-facing (vertical) window and an average daily temperature of −5°C with an inside temperature of 20°C. What is the efficiency of this heating method?

Solution

From Table 8.2, the average January daily insolation on a south-facing vertical surface is 11.2 MJ/m^2. For a $(1.5 \times 2.5)\text{m}^2 = 3.75\ \text{m}^2$ window, the total incident energy is $(11.2\ \text{MJ/m}^2) \times 3.75\ \text{m}^2 = 42$ MJ per day. The energy loss is obtained from equation (8.5) by multiplying the power per unit area by the area and the time; that is,

$$E = \frac{(T_\mathrm{h} - T_\mathrm{c})At}{R}.$$

For a standard double-pane window, the R-value is 0.35 (s·m^2·°C)/J. Using area in square meters, time in seconds (86,400 s/d), and the temperature difference in degrees °C yields energy in J. Thus

$$E = \frac{(20°\text{C} - (-5°\text{C})) \times (3.75\ \text{m}^2) \times\ (86{,}400\text{s/d})}{0.35\ (\text{s} \cdot \text{m}^2 \cdot °\text{C})/\text{J}} = 23.1\ \text{MJ per day}.$$

The net energy gain from passive solar heating is 42.0 MJ − 23.1 MJ = 18.9 MJ per day. This is compared to the total incident energy to give an efficiency of 100 × (18.9 MJ)/(42.0 MJ) = 45 %.

incident energy is 0.5 × 42 MJ = 21 MJ per day, resulting in a net energy loss through the window. This calculation also emphasizes the significance of a high R-value and the effects of lower outside temperatures.

8.8 Transpired Solar Collectors

A transpired solar collector, sometimes called a "solar wall" after the trade name SolarWall© of Conserval Engineering Inc. (Toronto, Ontario and Buffalo, New York), which markets this device, is a means of improving passive solar heating without the complexity and maintenance costs of flat plate or evacuated tube systems. Large industrial or office buildings (rather than small residential buildings) with a large (mostly window-free) south-facing wall, in a cool, sunny region with a central ventilation/heating system are ideal for the application of this technology.

The transpired solar collector consists of a dark perforated metal facade with about a 15-cm-air-space between the collector and the building wall. Figure 8.13 shows

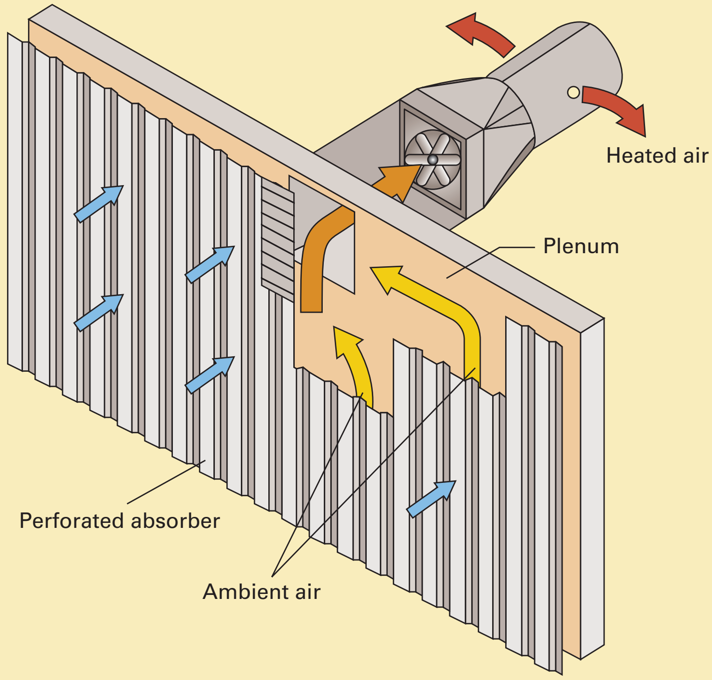


Figure 8.13: Design of a transpired solar collector.

NREL, Solar Buildings, http://www.nrel.gov/docs/fy06osti/29913.pdf

the basic design of a transpired solar collector. Solar radiation heats the dark absorber, and as air is pulled into the building for ventilation and heating, it is heated as it passes through the perforated solar wall. The fan shown in the figure, which draws air through the collector, may be a component of the building's ventilation system or may be an additional fan associated with the collector. Air entering the building can be heated by as much as approximately 22°C compared to the ambient outside air temperature, and the collector can provide up to 2.7 GJ/m^2 per year of additional heat to the building. Preheating ventilation air reduces the heating requirements for the building.

Figure 8.14 on the next page shows the operation of the transpired solar collector in the winter and summer. In the winter, air preheated by the collector is drawn into the building, thereby reducing the load on the heating system. In the summer, ventilation air is drawn directly into the air conditioning system without being heated by the transpired collector.

Transpired solar collectors may be retrofitted to existing buildings that meet the requirements for this technology. They are readily incorporated into the design of many new buildings, and their installation cost, in this case, is partially offset by the reduced cost of a finished surface for the facade. A typical transpired solar collector installation that was incorporated into the original building design is illustrated in Figure 8.15 on the page 289. A transpired solar collector that was retrofitted on the roof surface of a sports center is shown in Figure 8.16 on the page 289.

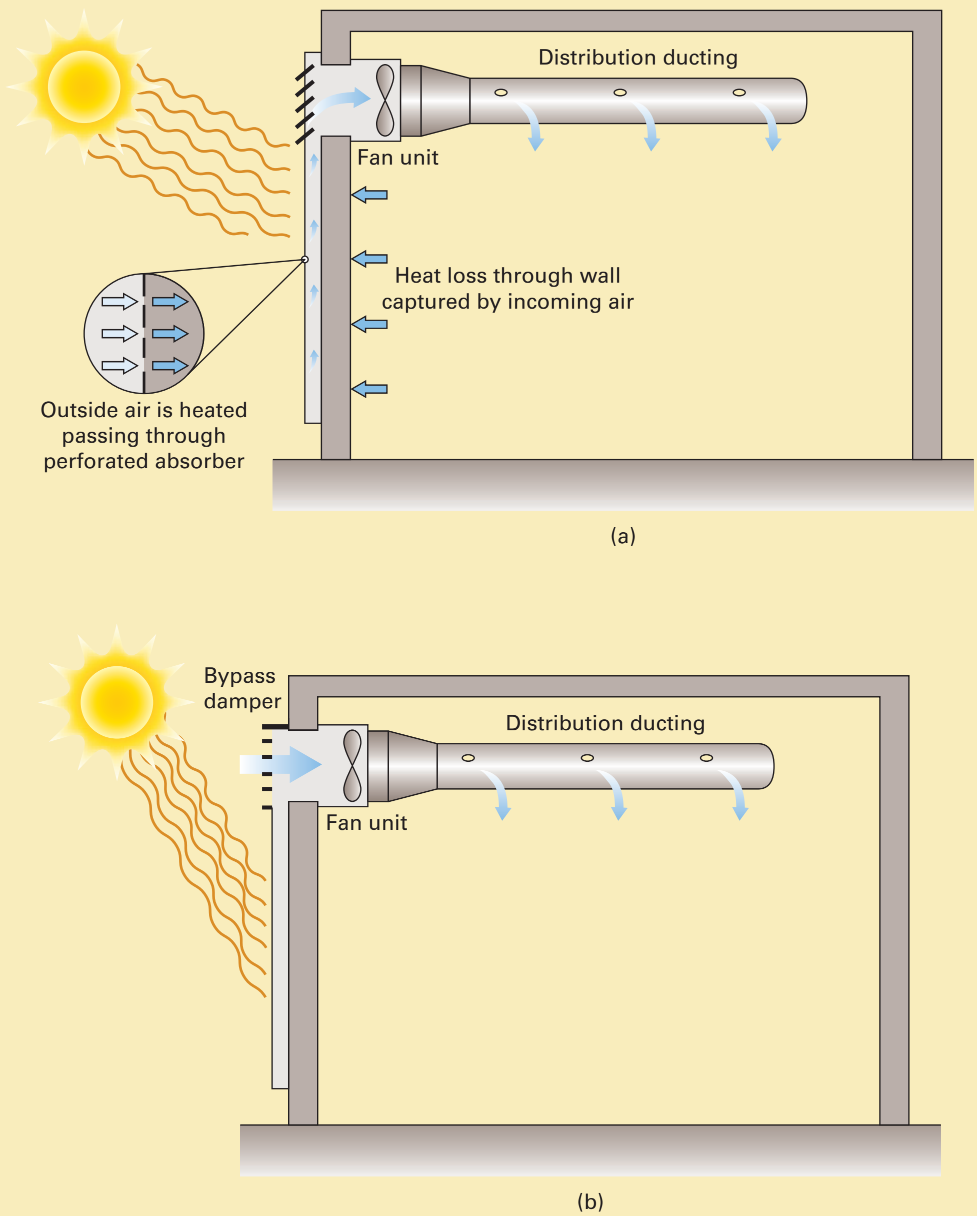


Figure 8.14: Operation of a transpired solar collector in winter (a) and in summer (b).

U.S. Department of Energy, Transpired Collectors (Solar Preheaters for Outdoor Ventilation Air), http://www1.eere.energy.gov/femp/pdfs/fta_trans_coll.pdf

Figure 8.15: Transpired solar collector on the south- and west-facing walls of the Mona Campbell Building at Dalhousie University, Halifax, Nova Scotia, Canada. This building has LEED Gold certification (see Energy Extra 17.1).

Richard A. Dunlap

Figure 8.16: Transpired solar collector on the Sportsplex, Dartmouth, Nova Scotia. The 300 m^2 collector is the dark section of the roof near the center of the building.

Richard A. Dunlap

8.9 Summary

The chapter has reviewed the properties of sunlight. Based on the total power radiated by the sun, the insolation at the surface of the earth, averaged over time and all locations, was found to be 168 W/m^2.

To describe how solar energy can be used for heating purposes, the chapter reviewed the three heat transfer mechanisms: conduction, convection, and radiation. The power transferred by conduction per unit area of a material is given as $P/A = \Delta T/R$, where ΔT is the temperature difference, and R is the R-value, defined as the thickness of the material divided by the thermal conductivity. R-values for insulating materials allow for the convenient calculation of heat transfer through walls, windows, and other building components. Radiative heat transfer is described by the Stefan-Boltzmann law and is proportional to the fourth power of the absolute temperature of an object.

A flat plate solar collector is a box in which solar energy is transferred to a working fluid for distribution to a building for space heating or hot water needs. The efficiency of the solar collector can be evaluated on the basis of the radiative and conductive heat mechanisms that transfer thermal energy into and out of the collector.

The chapter evaluated the usefulness of solar heating on the basis of heating requirements for a building. The energy needed for heating purposes is a function of the size of the building and the quality of its construction, as well as the local climate. The effects of climate are quantified using degree days, where one degree day is one day during which the outside temperature is one degree below a standard inside temperature. Annual heating needs are determined by the number of degree days integrated over the year. As illustrated in the chapter, the utilization of the roof area of a single-family home for solar collectors is sufficient to make a reasonable contribution to space heating needs.

The periodic nature of sunlight, on both a daily and a seasonal scale, as well as the variability of heating requirements, again on a daily and seasonal scale, means that the efficient utilization of solar energy requires some method of thermal energy storage. The chapter discussed the effectiveness of different materials for heat storage in terms of their heat capacity and the possible mechanisms for transferring heat into and out of the storage system.

The chapter described the effectiveness of passive solar heating in terms of the trade-off between energy gain and energy loss through a window. Passive solar heating features can be incorporated into new building designs, often at little expense by utilizing specific design characteristics, building location, and/or orientation.

Problems

8-1 Calculate the power radiated by a woodstove of dimensions 65 cm high by 55 cm deep by 85 cm wide with a surface temperature of 120°C. Assume that heat is radiated from all surfaces of the stove and that the stove has an emissivity of 1. Note that woodstoves are painted black because black surfaces have high absorptance, and objects with high absorptance also have high emissivity.

8-2 Locate information about the current cost of home heating oil or natural gas in your area (whichever is in common use) and the cost of residential electricity. Assuming an efficiency of 85% for an oil furnace and 100% for electric heat, calculate the relative cost of electric heat compared with oil heat or natural gas if both heating systems require the same net energy to heat a house.

8-3 Consider a vertical south-facing window in a house at 40°N latitude. For an interior temperature of 20°C, make a plot of the minimum *R*-value as a function of outside temperature from −30°C to 10°C for which the passive solar heating exceeds the heat loss through the window.

8-4 Compare the total solar energy received at the surface of the earth in one year to the total annual global energy requirements.

8-5 Compare the *R*-values of:

(a) Two pieces of 3-mm-thick glass in thermal contact.

(b) Two pieces of 3-mm-thick glass with a 1-cm-air-space between them.

8-6 Approximate a house as a cube with an edge length of 7 m. The house loses heat from the four walls and the roof (but not the floor). The average *R*-value for the walls and roof is $R = 1.2$ (this takes into account walls, windows, doors, etc.). Calculate the heat loss in MJ/m^3 per degree day (°C), and compare this to the estimated residential heating needs discussed in this chapter.

8-7 A 300 liter (U.S.) electric hot water heater uses 9000 W of power to heat water. If the heater is filled with water at an initial temperature of 10°C, how long will it take for the water to reach 60°C? Assume there are no heat losses.

8-8 Compare the masses and volumes of water, concrete, sand, and wood needed to store 1 GJ of heat if the operating temperatures are $T_c = 30$°C and $T_h = 80$°C. In each case, calculate the edge length of a square storage unit with a height of 2.5 m.

8-9 Consider a house that is approximated as a cube that is 8 m on a side and has no windows. The house loses heat from the four walls and the roof. For an inside temperature of 20°C and an outside temperature of −20°C, it is desired to keep the total heat loss less than 5 kW. What is the minimum R_{SI}-value that is required for the walls and roof?

8-10 A cylindrical water tank 1.5 m in diameter and 2.5 m high is surrounded on both ends and the sides with $R_{SI} = 3$ insulation. It is desired to keep the water at 80°C, while the ambient temperature is 20°C. What is the minimum wattage of an electric heater that needs to be placed inside the tank?

8-11 The average monthly temperatures in Anchorage, AK are given in the table below. Calculate the heating degree days per year, and compare the results with the information in Table 8.4

month	average temperature (°C)
January	−8.5
February	−6.5
March	−4.0
April	+2.5
May	+8.5
June	+12.5
July	+15.0
August	+13.5
September	+9.0
October	+1.0
November	−5.5
December	−7.5

8-12 (a) Calculate the power transferred through a 10-cm-diameter iron rod that is 1 m long and is held at 0°C on one end and 20°C on the other end.

(b) It is desired to reduce the power transferred through the rod to 4 W by reducing the diameter of the rod. What should the new diameter be?

8-13 A two storey house in Portland, ME with dimensions 8.5 m by 12.0 m with a height of 7.0 m is heated electrically. The cost of electricity is 0.11 per kWh. Estimate the annual heating cost.

8-14 A house is heated with electricity at a cost of $0.10 per kWh. The building has 20 m^2 of double-glazed windows with an R_{SI} value of 0.4. A mechanism is constructed that covers the windows with 10 cm of polystyrene foam at night (i.e., for 12 hours per day) during six months of the year. If the outside temperature is constant at 0°C and the inside temperature is kept at 20°C, calculate the annual savings from this approach.

8-15 A wood stove has a total surface area of 1.5 m^2 and radiates a power of 1.0 kW. Make a plot of its surface temperature in °C as a function of emissivity.

8-16 A window with an R_{SI}-value of 0.18 receives 300 W/m^2 of insolation. If the interior of the building is at 20°C, what is the minimum outside temperature for which there is a benefit from passive solar heating?

8-17 A wall consists of 3.0 cm of exterior wood and 2.0 cm of interior wood separated by a 15 cm layer of polystyrene foam. If the interior is kept at 19°C, calculate the outside temperature for which the heat loss through the wall is 10 W/m^2.

8-18 A homeowner in Allentown, PA installs a 60° south-facing solar collector that (on the average over the year) replaces 1 kW of electric heat (purchased from the public utility at $0.11 per kWh). The homeowner is considering adding a tracking mechanism to maintain perpendicular alignment of the collector with the solar insolation. If the payback period for the upgrade is expected to be five years, what should the homeowner be willing to pay for the tracking device? Comment on this plan.

8-19 A homeowner sells an electrically-heated 280-m^2 home with 3.2-m-high ceilings in Minneapolis and purchases an identical home in San Francisco. Estimate the expected savings in annual heating costs.

8-20 A home uses a concrete floor to store passive solar energy. If the floor heats to 40°C during the day and cools to 20°C at night, calculate the thickness of concrete needed to store the amount of energy from Example 8.7 if the floor's area is 150 m^2.

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CHAPTER 9

Electricity from Solar Energy

Learning Objectives: After reading the material in Chapter 9, you should understand:

- The generation of electricity from solar energy through heat engines.
- The basic physics of semiconducting materials and the properties of n-type and p-type materials.
- The construction of a semiconducting junction device.
- The production of electricity through the interaction of photons on semiconducting junctions.
- The sensitivity and efficiency of photovoltaic devices.
- The application of photovoltaic devices for electricity generation worldwide.
- The availability of solar energy and economic viability of its utilization.

9.1 Introduction

The extent of the solar energy resource was illustrated in the previous chapter. However, the applications presented thus far, which utilize thermal energy extracted from solar radiation, are most suitable for residential space heating. The conversion of solar energy into electricity allows for the wide-scale distribution of energy on the electric grid, in addition to local residential use. Two different approaches can be taken to the conversion of solar energy into electricity: (1) the conversion of solar radiation into heat, followed by the conversion of heat into mechanical energy by means of a heat engine, and finally the generation of electricity by means of a generator; (2) the direct conversion of radiation into electrical energy by means of a photovoltaic device. These two approaches are discussed in this chapter.

9.2 Solar Electric Generation

A relatively straightforward (at least conceptually) method of producing electricity from solar energy is to use the heat produced in a solar collector to generate electricity by means of a heat engine. This is the most easily accomplished when water is heated above its boiling point to produce steam that can then be used to drive a steam turbine. Focusing collectors are necessary for this purpose because flat plate collectors are

Adrian Lyon/Alamy Stock Photo

not suitable for achieving the required temperatures. Several approaches to large-scale focusing collector designs have been taken in the past. The most notable are:

- Parabolic troughs.
- Parabolic dishes.
- Central receivers.

These three devices are now reviewed briefly.

9.2a Parabolic Troughs

Parabolic trough collectors heat a fluid that is flowing through a pipe located at the focus of a parabolic trough (Figure 9.1). The parabolic troughs rotate to track the sun to ensure that the radiation is properly focused on the fluid-carrying pipes. In this arrangement, the fluid is typically oil, and the heated oil transfers its thermal energy to water through a heat exchanger to produce steam. The overall efficiency of converting solar energy to electrical energy is limited by the Carnot efficiency based on the hot and cold reservoir temperatures. The largest parabolic solar trough project is located in the Mojave Desert in California and has a maximum rated capacity of 354 MW_e. A number of parabolic trough systems have been constructed worldwide, and Table 9.1 lists the major operational facilities. As the table indicates, much of the activity in this field has occurred in the southwestern United States and in Spain.

9.2b Parabolic Dishes

An alternative to the parabolic trough geometry is the parabolic dish geometry (Figure 9.2). Units may be either individual parabolic dishes or arrays of dishes. Instead of a line focus, as is the case for the parabolic trough, the parabolic dish has a point focus. These are tracking collectors and utilize one of two different approaches to converting solar energy into electricity. The Solar Total Energy Project (STEP) in Shenandoah, Georgia heated water to produce steam to generate electricity through

Figure 9.1: Parabolic trough solar collectors at Kramer Junction, California.

RGB Ventures/SuperStock/Alamy Stock Photo

Table 9.1: Major operational parabolic trough solar projects (≥ 150 MW_e) as of 2016.

name	location	maximum capacity (MW_e)
Solar Energy Generating Station (SEGS)	Mojave Desert, California	354
Mojave Solar Project	Harper Dry Lake, California	280
Solana Generating Station	Gila Bend, Arizona	280
Genesis Solar Energy Project	Blythe, California	250
Solaben Solar Power Station	Logrosán, Spain	200
NOOR 1	Ouarzazate, Morocco	170
Andasol 1	Andalusia, Spain	150
Extresol	Torre de Miguel Sesmero, Spain	150
Solnova Solar Power Station	Sanlúcar la Mayor, Spain	150

Figure 9.2: Array of parabolic dish solar collectors at Maricopa Solar Project in Peoria, Arizona. The facility consists of a total of 60 parabolic dishes.

Brian Green/Alamy Stock Photo

conventional generators. This facility is no longer functional. Another approach is to directly convert the energy content of hot gas produced by the absorption of solar radiation into mechanical energy using a Stirling engine. Figures 9.2 and 9.3 show the Stirling-engine-based parabolic dish array at the Maricopa Solar Project in Peoria, Arizona. The solar-to-electric efficiency for this system is around 26% and is limited primarily by the Carnot efficiency.

Example 9.1

Calculate the average power per unit area that is incident on a 5-cm-diameter focal area for a 10-m-diameter parabolic dish as illustrated in Figure 9.3. Assume a midday insolation of 650 W/m^2 on a sunny day.

Continued on page 297

Example 9.1 continued

Solution

A 10-m-diameter dish has an area of

$$\frac{\pi(10\text{ m})^2}{4} = 78.5\text{ m}^2,$$

giving a total insolation on the dish of

$$(78.5\text{ m}) \times (650\text{ W/m}^2) = 51\text{ kW}.$$

If this is focused on an area of

$$\frac{\pi(0.05\text{ m})^2}{4} = 1.96 \times 10^{-3}\text{ m}^2,$$

then the power per unit area is

$$\frac{51\text{ kW}}{1.96 \times 10^{-3}\text{m}^2} = 26\text{ MW/m}^2.$$

Figure 9.3: Parabolic dish solar collectors at Maricopa Solar Project in Peoria, Arizona showing the Stirling engine used to convert heat to mechanical energy.

DOE Photo/Alamy Stock Photo

9.2c Central Receivers

Another possibility for the conversion of solar energy to electricity by means of a heat engine is by means of a central receiver. This is analogous to a single large parabolic dish except that the parabolic dish is replaced with a planar array of computer-controlled mirrors, each of which tracks the sun and reflects the sunlight onto a single point. The individual mirrors are referred to as *heliostats*, and the central receiver is contained in the so-called *power tower*. An early example of this type of design is Solar One in California, which operated between 1982 and 1986. This was later redesigned to become Solar Two (Figures 9.4 and 9.5). Solar Two operated from 1995 to 1999 and achieved its rated output of 10 MW_e. A working fluid, circulated through the focal point at the top of the tower, is used to produce steam to either drive a turbine/generator to generate electricity directly or as a mechanism to store thermal energy for later use (Figure 9.6). Solar One used oil for heat storage, and Solar Two used a molten salt.

More recent examples of central receiver systems include the PS10 and PS20 facilities in Spain (Figure 9.7 on the page 300). PS10, rated at 11 MW_e, became operational in 2007, and PS20, rated at 20 MW_e, became operational in 2009. Both facilities are currently operational.

The largest central receiver solar power plant at present is the Ivanpah Solar Power Facility located at the base of Clark Mountain in the Mojave Desert in California, which became operational in 2014. This facility consists of three central tower receivers (Figure 9.8 on the page 300) and 173,500 heliostats with a total surface area of 2.44 km^2. The total capacity of the three units is 377 MW_e.

Figure 9.4: Solar Two in Daggett, California. The scale can be determined from the central tower that is about 90 m high.

Aerial Archives/Alamy Stock Photo

Figure 9.5: One of Solar Two's heliostats. The Solar Power Tower is reflected in the mirror.

DOE Photo/Alamy Stock Photo

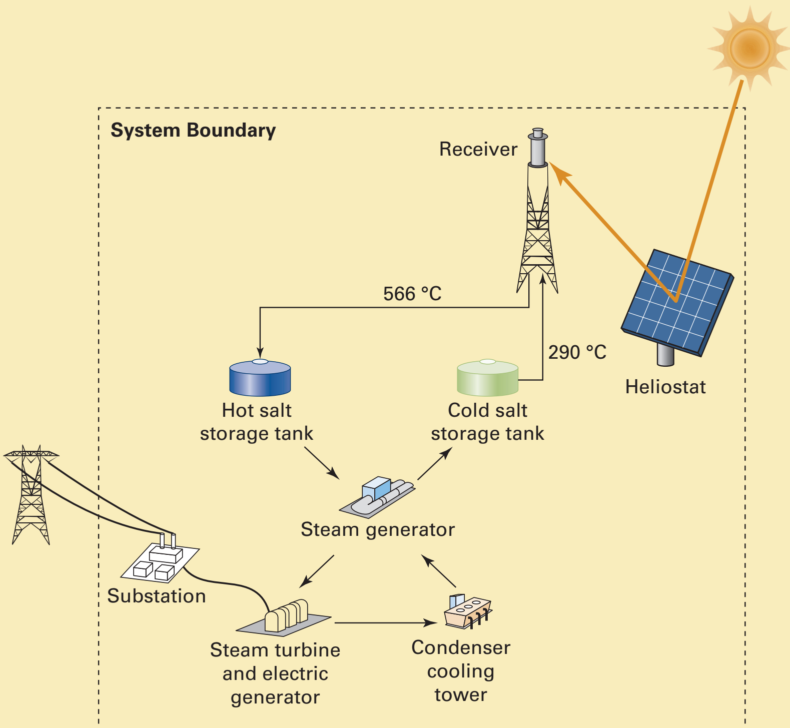


Figure 9.6: Schematic diagram showing the operation of Solar Two.

U.S. Department of Energy

Figure 9.7: The PS10 rated at 11 MW_e (foreground) and PS20 rated at 20 MW_e (background) solar generating stations at Sanlúcar la Mayor near Seville in Andalusia, Spain.

Figure 9.8: Three collector towers at the Ivanpah Solar Electric Generating Station in the Mojave Desert in California.

9.2d Solar Ponds

A solar pond is a saltwater pond, which may be natural or artificial, that provides a means of storing thermal energy from the absorption of solar radiation. The salt forms a natural vertical gradient in the pond, where denser high-salinity water sinks to the bottom while less dense low-salinity water floats on the top. The total salt content is adjusted so that the salt solution near the bottom of the pond is saturated.

When sunlight is incident on the pond, it passes through the water, is absorbed by the bottom, and is converted into thermal energy. This thermal energy heats the lower layer of the water. Normally this heated region of water at the bottom of the pond would rise (since the warmer water has a lower density) and create convection currents that would mix the more saline water with the less saline water above it. However, because the bottom region of the pond is a saturated salt solution, there is no salinity gradient there, and this inhibits convective mixing with the layers above. This feature traps the heat in the lower portion of the pond and creates a thermal difference between the bottom and top layers of the pond, where the bottom can typically reach temperatures of up to 90°C while the top may be at 30°C. While the thermal energy contained in the bottom regions of the pond can be used as a direct source of heat, the temperature difference between the bottom and top of the pond can be used to run a heat engine and generate electricity. Although the hot water does not boil to produce steam to operate a turbine directly, heat exchangers (Figure 9.9) can transfer the thermal energy of the hot water to

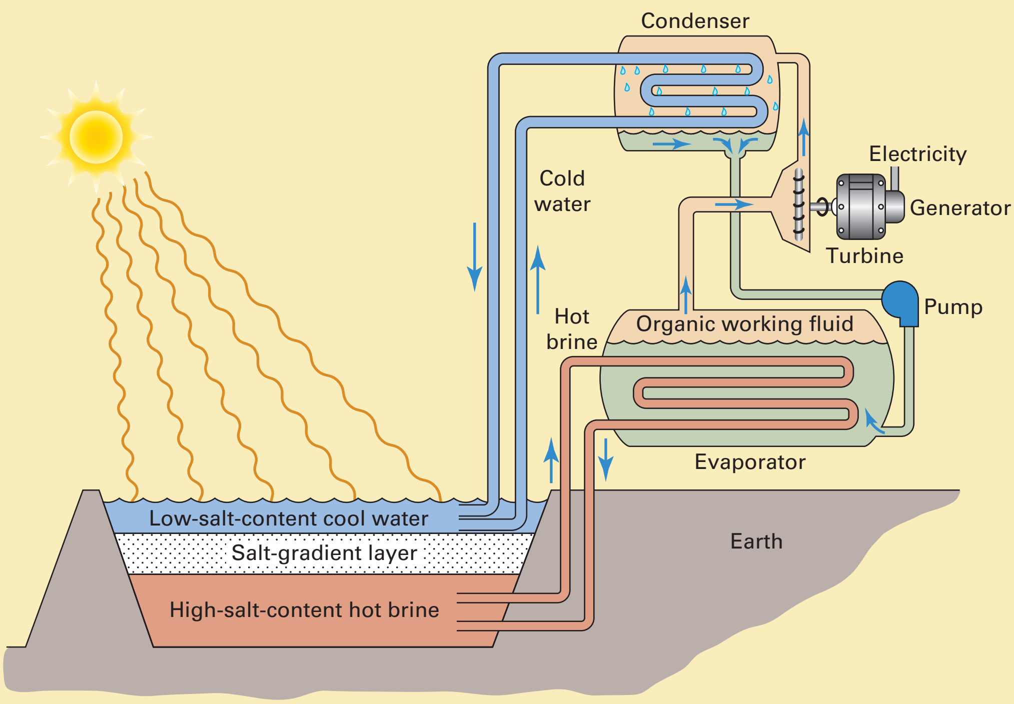


Figure 9.9: Method of electricity generation using a solar pond.

Based on Quora, How does a solar pond work?, https://www.quora.com/How-does-a-solar-pond-work a working fluid with an appropriate phase diagram that can be used to drive a turbine/generator. The cold surface water serves as the cold reservoir of the heat engine, as the figure shows.

A number of experimental solar ponds have been constructed worldwide. The largest solar pond thus far was operated in Beit HaArava, Israel in the 1980s. It had an area of about 0.2 km^2 and produced an electrical output of 5 MW_e. An ongoing experimental solar pond (Figure 9.10) has operated in El Paso, Texas since 1987. It has an area of 3,200 m^2 and has been used as an experimental facility to improve solar pond technology.

One advantage of this approach to generating electricity from solar radiation is that the large thermal mass of the water in the pond evens out fluctuations between sunny and cloudy days and between day and night. On the other hand, the relatively small temperature difference between the hot and cold reservoirs (compared to that for most thermal generation schemes) means that the thermodynamic efficiency is low. Solar ponds are of particular interest in developing countries because the simple technology has relatively low infrastructure and operating costs.

Other approaches to the use of salinity gradients for the production of electricity are discussed in Chapter 14.

Figure 9.10: El Paso solar pond.

Huanmin Lu, Andrew H. P. Swift, Herbert D. Hein and John C. Walton "Advancements in Salinity Gradient Solar Pond Technology Based on Sixteen Years of Operational Experience" J. Sol. Energy Eng 126 (2004) 759–767 doi:10.1115/1.1667977. Courtesy Herbert D. Hein, Jr.

ENERGY EXTRA 9.1

Solar updraft towers

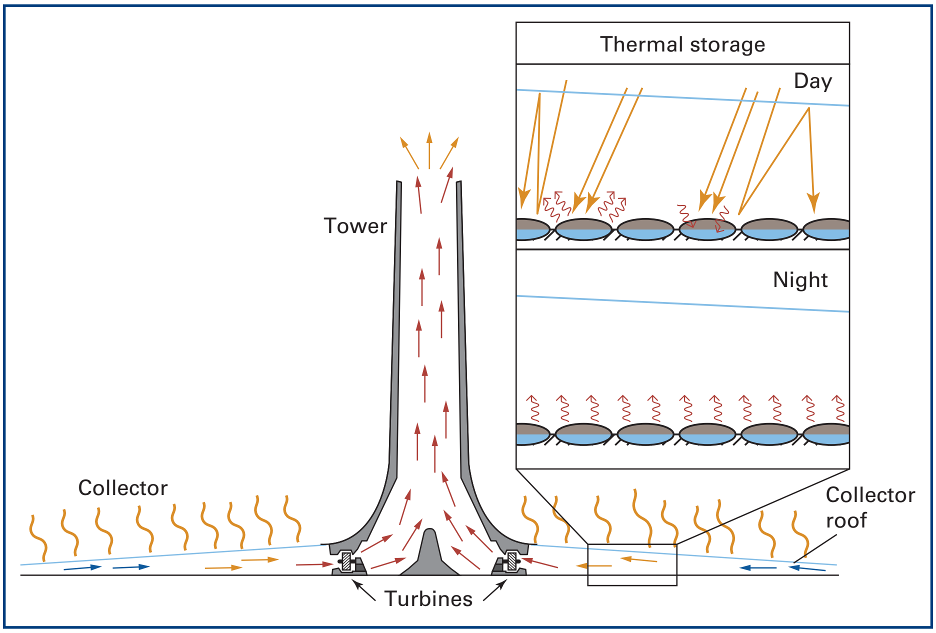
The solar updraft tower is an interesting approach to harnessing energy from the sun. The concept was first proposed in 1903 by Isidoro Cabanyes, a colonel in the Spanish Army. The general design is illustrated in the diagram. A large greenhouse is created by suspending a transparent sheet a few meters above the ground, as the illustration shows. The sun heats the air beneath the canopy, which is drawn through a set of turbines and up a tall chimney or tower. The air is drawn up the chimney because it has lower density (since it is warmer) than the air higher up in the atmosphere (see Figure 4.6). This phenomenon, called the chimney effect or stack effect, has been known for many years. This effect can be quantified, approximately, by the pressure difference, ΔP, driving the air through the turbines as

$$\Delta P = Cah\left[\frac{1}{T_{out}} - \frac{1}{T_{in}}\right],$$

where a is the atmospheric pressure, h is the height of the chimney, T_{out} is the temperature outside of the canopy, and T_{in} is the temperature inside the canopy. The constant a in SI units has the value 0.0342 K/m. This expression emphasizes the need for a tall chimney and an effective greenhouse effect to optimize the temperature difference between the inside and outside.

The solar updraft tower concept was demonstrated very successfully by a prototype device constructed in Spain in 1982. It consisted of a solar tower 195 m in height and 10 m in diameter. The greenhouse covered an area of 0.046 km^2. While the tower was designed as a three-year test project, it actually operated until 1989, when it collapsed due to rusting support wires. It produced a maximum electrical output of about 50 Kw, corresponding to about 1 W/m^2 of collector. Compared to an average insolation worldwide of 168 W/m^2, the experimental solar updraft tower achieved an efficiency of less than 1%.

Low efficiencies are, in general, a drawback of solar updraft towers. Simulations have predicted efficiencies of, at most, a few percent, much less than efficiencies of 15% or more for photovoltaics

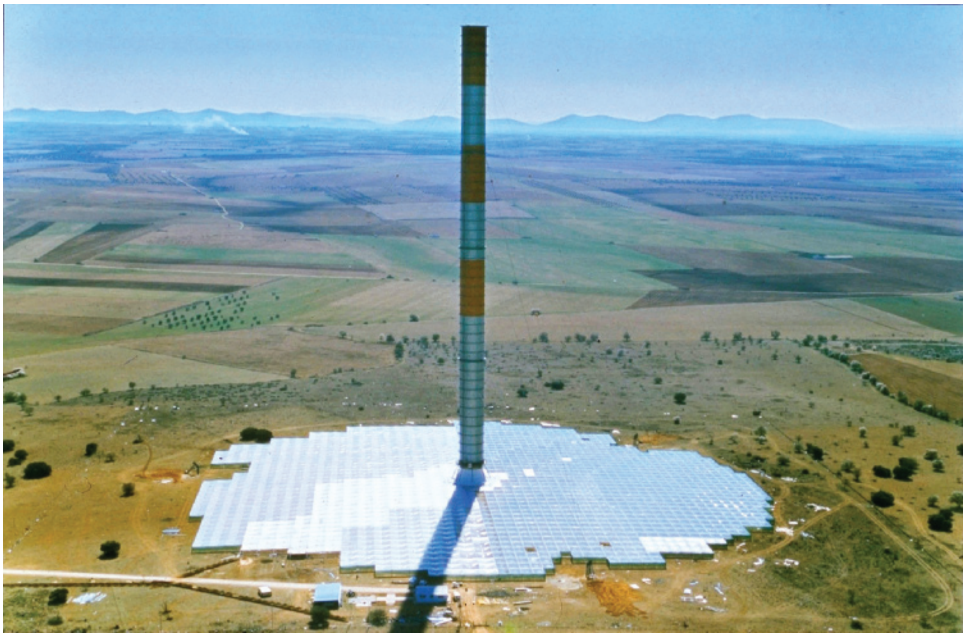


Based on Kilohn limahn, https://fr.wikipedia.org/wiki/Fichier:Sch%C3%A9ma_fonctionnel.jpg

The operational concept of the solar updraft tower.

Continued on page 304

Energy Extra 9.1 continued

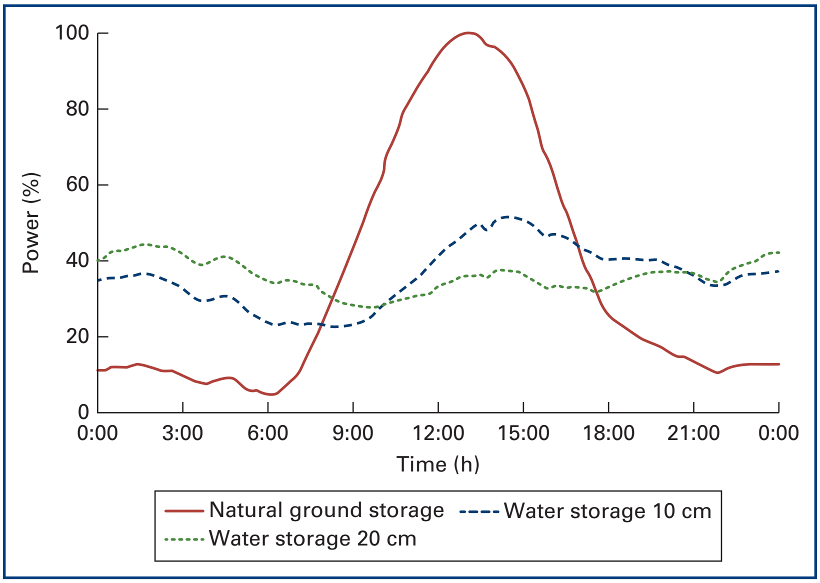


Courtesy of sbp

Experimental solar updraft tower in Manzanares, Spain.

(see Sections 9.3 to 9.5). As well, infrastructure costs are high, and larger devices are expected to be beneficial from an economic standpoint. On the other hand, updraft towers utilize a relatively simple technology and are expected to have low operational costs.

A potential problem with solar electricity is the requirement for energy storage because of the



Based on Schlaich Bergermann Solar GmbH, Schwabstr. 43, 70197 Stuttgart info@sbp.de, http:\\ www.solar-updraft-tower.com

Schlaich Bergermann Solar GmbH, Schwabstr. 43, 70197 Stuttgart.

Continued on page 305

Energy Extra 9.1 continued

intermittent nature of the resource. For the solar updraft tower, the use of thermal storage can even out electricity generation, as the diagram illustrates. Containers of water cover the ground underneath the canopy. During the day solar energy heats both the air under the canopy, thereby generating electricity, and the water. At night the warm water transfers heat to the cooler atmosphere, providing a temperature differential to draw air through the turbines. This approach evens out the fluctuations in insolation during the day.

Topic for Discussion

A recent study has considered the possibility of constructing a 200 MW_e solar updraft tower in Western Australia. The chimney would be 1 km high, and the greenhouse would have a diameter of 10 km. The estimated capital cost would be about $1.67 billion. Discuss the efficiency of the device based on its area, the average insolation, and the rated output. If operating costs are minimal, discuss the payback period, including the cost recovery factor, such that the price of electricity per kWh would be competitive with other renewable technologies.

9.3 Photovoltaic Devices

An alternative approach to the production of electricity from sunlight using a heat engine is *photovoltaics*. An attractive aspect of photovoltaics is the ability to implement this technology on a wide range of scales from milliwatt devices suitable for running watches and pocket calculators (Figure 9.11) to multimegawatt installations (Figure 9.12 on the next page). The operation of a photovoltaic device results from how light interacts with the electrons in a semiconducting material. The description of this behavior begins with an overview of some basic semiconductor physics.

Electrons that are associated with an atom may be described in terms of energy levels. For the hydrogen atom, the electron can occupy quantized levels with energies that are given by the expression

$$E = -\frac{me^4}{8\varepsilon_0^2 h^2 n^2}, \tag{9.1}$$

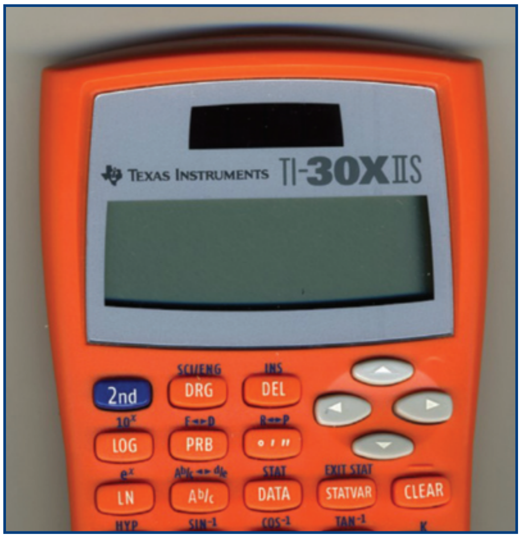


Figure 9.11: Photovoltaic device (black area above the model number) used to power a pocket calculator. The 1.5-cm^2 cell produces about 10 mW_e in bright sunlight.

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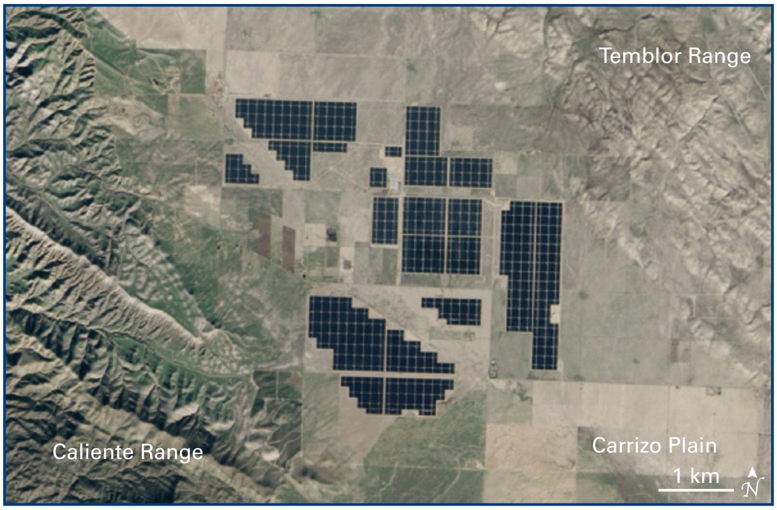


Figure 9.12: Image from space of the Topaz Solar Farm, a 550 MW_e photovoltaic installation covering 25.6 km^2 on the Carrizo Plain in southern California. Note the distance scale on the lower right in the image.

NASA

where e is the charge on the electron, m is the mass of the electron, ε_0 is the permittivity of vacuum, h is Planck's constant, and n is an integer that defines the energy level. Equation (9.1) is sometimes written as $E = -hcR/n^2$, where R is the Rydberg constant ($R = 1.097 \times 10^7$ m^{-1}). Increasing values of n correspond to increasing energy [Figure 9.13(a)]. In an atom that contains many electrons, the interactions between the electrons cause the energy levels to split into sublevels [Figure 9.13(b)]. The sublevels are labeled s, p, d, f, and so forth, as shown in the figure, and correspond to different values of the orbital angular momentum. An s-sublevel can hold 2 electrons, a p-sublevel can hold 6, a d-sublevel can hold 10, an f-sublevel can hold 14, and so

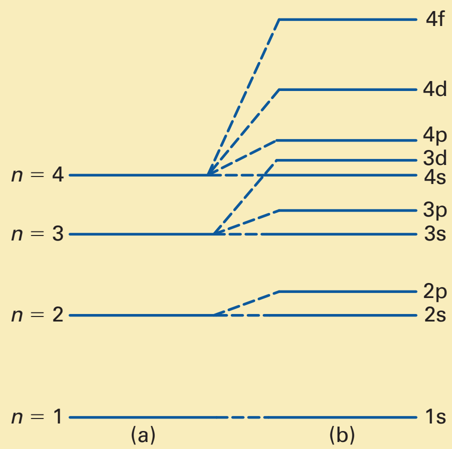


Figure 9.13: Energy levels in (a) hydrogen atom and (b) a multielectron atom.

Based on R. A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks Cole, 2003.

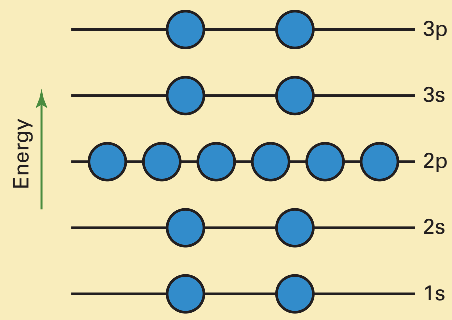


Figure 9.14: Occupation of electron energy levels in a Si atom in its ground state. The circles represent electrons.

on. Silicon (Si), which has 14 electrons, is a good example of a common semiconducting material. The electrons in their lowest energy configuration (ground state) can be expressed as

$$1s^2 2s^2 p^6 3s^2 3p^2, \tag{9.2}$$

where 1s, 2s, 2p, and so on represent the energy sublevels, and the superscript after the level name gives the number of electrons in that level [Figure 9.14]. The two 3s electrons and two 3p electrons are not as firmly bound to the Si atom as the other electrons and are referred to as *valence electrons*.

If a large number of Si atoms are assembled to form a solid, then the interactions between the electrons associated with one atom and the electrons associated with another atom cause the energy levels to change a little—sometimes a bit lower, sometimes a bit higher. Thus, the energy levels get smeared out into *bands* (Figure 9.15). For a single Si atom, the 1s level can hold 2 electrons. For a piece of

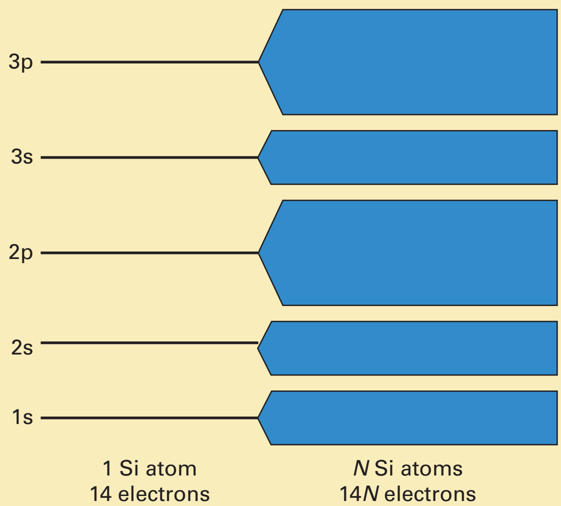


Figure 9.15: Energy bands in a piece of Si containing N Si atoms.

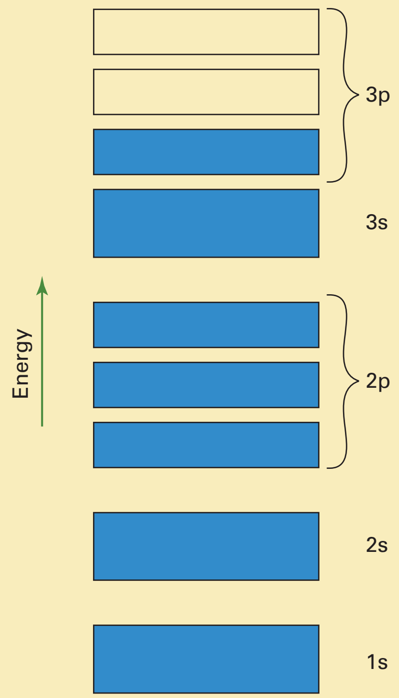


Figure 9.16: Band structure of a piece of Si. The solid boxes represent occupied bands, and the open boxes represent unoccupied bands.

Si containing *N* Si atoms, the 1s band can hold 2*N* electrons. Similarly, in the piece of Si, the 2s band holds 2*N* electrons, the 2p band holds 6*N* electrons, and so on. It turns out that the interactions in the solid also cause the 2p and 3p bands to split into three sub-bands, each of which can contain 2*N* electrons. Thus, the electrons in a piece of Si fill up the 1s, 2s, 2p, 3s, and the first of the three 3p sub-bands (Figure 9.16). The 2*N* electrons in the 3s band and the 2*N* electrons in the lowest of the 3p sub-bands are the valence electrons in a piece of Si containing *N* Si atoms. The second 3p sub-band in Si is called the *conduction band* and, as shown in the figure, is empty in the ground state (i.e., contains no electrons). The spaces (in energy) between the bands are regions where no energy levels exist and are forbidden energy regions for the electrons. The forbidden space between the valence band and the conduction band is called the *energy gap* (or *band gap*) and has a width corresponding to an energy E_g. The size of the energy gap depends primarily on the kind of material; for Si, it is 1.1 eV.

The valence electrons contribute to the bonding between the atoms in a piece of solid Si, as represented by the simple two-dimensional picture of the atoms in a Si lattice in Figure 9.17. Each Si atom shares its four valence electrons with its four neighbors.

It is now possible to describe how light interacts with electrons in a solid. As described in Chapter 1, light is quantized in the form of photons. Each photon has an energy related to the frequency of the light (the greater the frequency, the greater the

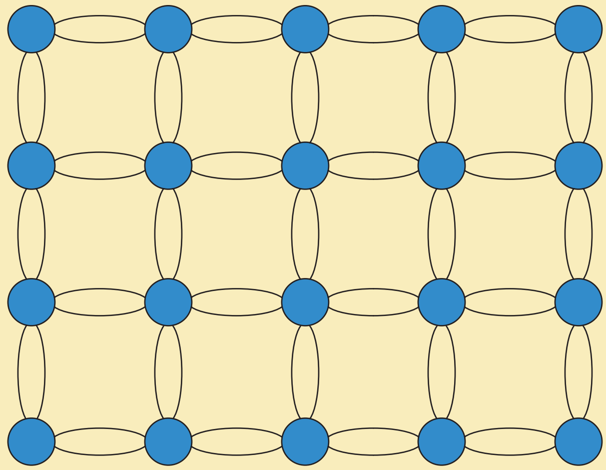


Figure 9.17: Two-dimensional representation of bonding in a piece of Si. Each of the lines between the atoms represents a 3s or 3p electron involved in bonding.

energy per photon [see equation (1.26)]. From equation (1.25), the energy per photon can be related to the wavelength of the light, λ, as

$$E = \frac{hc}{\lambda}. \tag{9.3}$$

In customary units, this is

$$E = \frac{1240 \text{ eV} \cdot \text{nm}}{\lambda}, \tag{9.4}$$

where E is in eV, and λ is in nm. If a photon of sufficient energy is incident on a piece of Si, it can impart that energy to an electron in the valence band of the material and cause it to move into an energy level in conduction band (Figure 9.18 on the next page). When the electron moves to the conduction band, it leaves a vacant energy state in the valence band. This vacant state has an effective positive charge and is referred to as a *hole*. To form the electron-hole pair, the photon must have energy greater than the energy gap. In Si, the energy gap of 1.1 eV corresponds [according to equation (9.4)] to a wavelength of 1130 nm. From Figure 8.1, it can be seen that most of the solar spectrum (including the entire visible region) satisfies this condition. A simplified picture of the lattice, illustrating electron-hole pair formation, is shown in Figure 9.19 on the next page. The electron formed in this way is not bound to any particular atom and is free to move about in the material. Similarly, the hole can move about by exchanging places with one of the valence electrons associated with the other Si atoms in the material. If a number of photons are incident on a piece of Si and form a number of electron-hole pairs, then these electrons and holes can move through the material and constitute an electric current. In this way, the energy associated with the photons in the radiation can be converted into electrical energy.

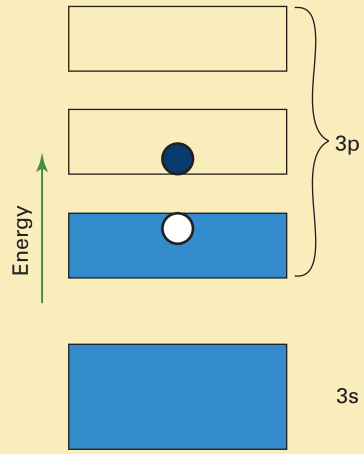


Figure 9.18: Band structure (upper portion only) of Si, showing the excitation of an electron from the valence band to the conduction band caused by the absorption of a photon of sufficient energy.

The preceding description may suggest a means of making a photovoltaic cell, but this approach presents a major problem. As the electron is negatively charged, the hole is effectively positively charged, and they can both move about in the material; these unlike charges attract and at some point are likely to combine and cancel each other out. This is called *recombination* and corresponds to a free electron in the conduction band (Figure 9.18), losing energy and falling across the energy gap to fill a hole in the valence band. This can be seen in the picture of the lattice in Figure 9.19, where an electron can fill a broken bond, thus eliminating both the free electron and the hole.

The design of a functional photovoltaic cell requires the elimination of recombination (as much as possible). Understanding how this may be done requires a

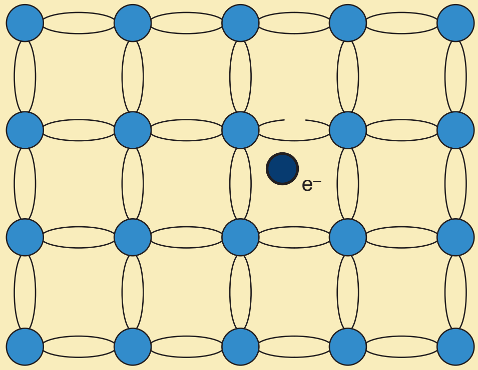


Figure 9.19: Portion of a Si lattice showing broken bond and resulting conduction electron.

Example 9.2

Estimate the range of photon energies that corresponds to the visible portion of the solar spectrum.

Solution

Figure 8.1 shows that the visible portion of the solar spectrum covers wavelengths between about 400 nm and 700 nm. From equation (9.4), these wavelengths correspond to the following energies:

For 400 nm: $\frac{1240 \text{ eV} \cdot \text{nm}}{400 \text{ nm}} = 3.1$ eV at the violet end of the visible spectrum.

For 700 nm: $\frac{1240 \text{ eV} \cdot \text{nm}}{700 \text{ nm}} = 1.8$ eV at the red end of the visible spectrum.

consideration of the effects of impurities in a semiconducting material. The behavior of an impurity phosphorus atom in a silicon lattice is considered first. Phosphorus has 15 electrons in the configuration $1s^2 2s^2 2p^6 3s^2 3p^3$. When a phosphorus atom replaces a silicon atom, the two 3s electrons from the valence band of the phosphorus atom take the place of the two 3s electrons from the valence band of the silicon atom that was removed. Two of the phosphorus 3p electrons take the place of the two Si 3p electrons, but this leaves one phosphorus 3p electron left over. There is no place for this to go in the silicon valence bands because they are filled up, so it goes into the conduction band [Figure 9.20(a)]. The difference between this picture and Figure 9.18 is that, in the present case, an electron appears in the conduction band

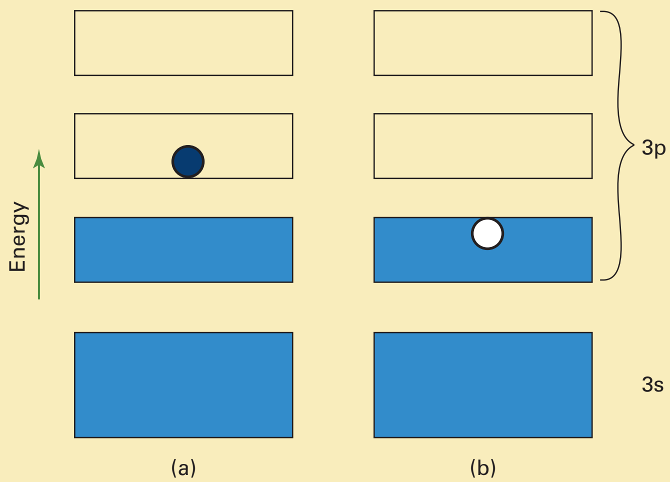


Figure 9.20: Occupied electron states in a piece of Si with (a) donor impurity and (b) acceptor impurity.

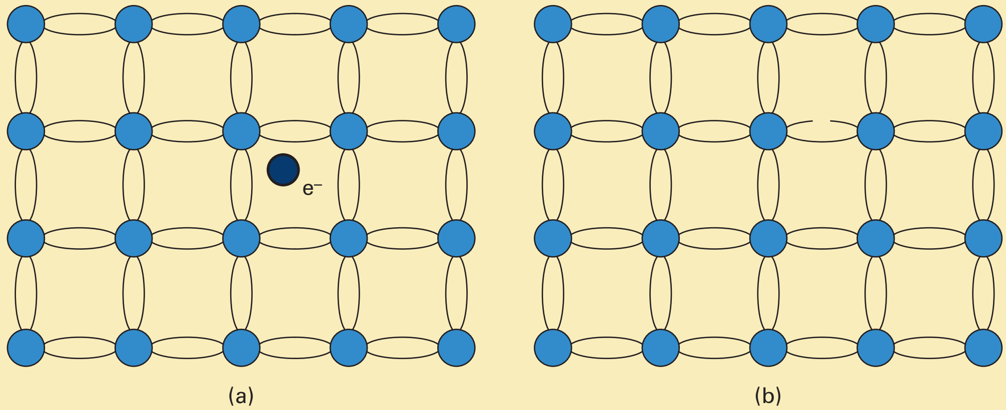


Figure 9.21: Portion of a Si lattice showing (a) conduction electron from donor impurity and (b) hole from acceptor impurity.

without the corresponding creation of a hole in the valence band. This situation is illustrated in Figure 9.21(a), where the phosphorus atom loses one of its localized valence electrons, and that electron is free to move about in the material. This leaves the phosphorus atom (now a positive phosphorus ion) with a missing electron and a corresponding positive charge. It is important to note that, as a whole, this material is electrically neutral because it is made up of atoms that were originally neutral. However, it is different than, say, a piece of pure silicon because a negatively charged electron is free to move about in the material, and a corresponding positively charged ion is fixed in its location in the lattice. The phosphorus atom is referred to as a *donor* because it gives up, or donates an electron to the conduction band, and the material is referred to as an *n-type* semiconducting material because there are free negatively charged electrons in the material.

In contrast, an aluminum impurity in silicon behaves differently. Aluminum has 13 electrons in the configuration $1s^2 2s^2 2p^6 3s^2 3p^1$. Thus there is one electron too few to fill up the 3s band and the first of the 3p valence bands. The lack of an electron results in the appearance of a hole in the 3p valence band without the corresponding appearance of an electron in the conduction band. This situation [Figure 9.20(b)] is in contrast to the electron-hole pair formation shown in Figure 9.18. Figure 9.21(b) shows the resulting formation of a hole associated with a missing bond in the silicon lattice. In general, this mobile hole moves through the material by exchanging places with localized electrons that form bonds between the silicon atoms. The movement of the hole means that the aluminum atom (now a negative aluminum ion) binds up an additional electron and becomes a negative ion. Again, the material is electrically neutral overall, but there will be a positive hole that can move about freely and a fixed negative ion to compensate for it. Aluminum in silicon is called an *acceptor*, and this material is a *p-type* material.

Semiconductors with impurities that behave as just described are referred to as *doped* semiconductors, compared with pure semiconducting materials, which are referred to as *intrinsic* semiconductors. Virtually all semiconducting devices

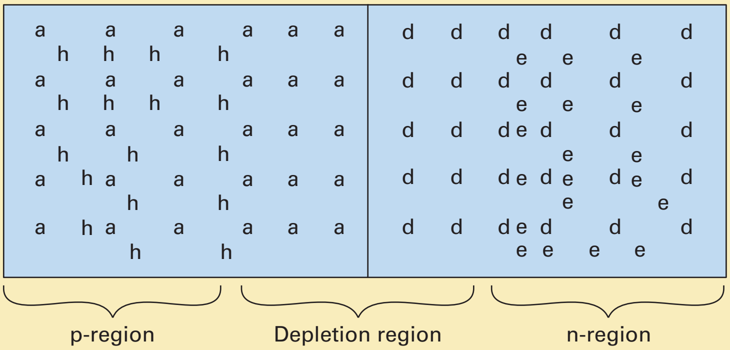


Figure 9.22: Semiconducting junction formed from a piece of p-type and n-type semiconducting material showing acceptor impurities (a), holes (h), donor impurities (d), and electrons (e).

Based on R. A. Dunlap, Experimental Physics. Modern Methods. Oxford University Press Inc, 1988

are constructed from combinations of n-type and p-type materials. The simplest arrangement of n-type and p-type materials is the semiconducting junction (or *diode*) (Figure 9.22), where a n-type material is in electrical contact with an p-type material. The charges in the system are shown in Figure 9.22: the negatively charged acceptor ions, the positively charged donor ions, the negatively charged electrons, and the positively charged hole. The neutral silicon atoms are not shown. Recall that the charged electrons and holes are free to move around, and the charged acceptor and donor ions are fixed in the lattice. The negatively charged electrons in the n-type material tend to move away from the junction because they are repelled by the negatively charged acceptor ions on the other side. Similarly, the positively charged holes in the p-type material tend to move away from the junction because they are repelled by the positively charged donor ions on the other side. Thus, as shown in the figure, a region around the junction (called the *depletion region*) is formed where there are no free electrons or holes.

If a photon of sufficient energy is incident on the depletion region, it can create an electron-hole pair as just described for pure silicon. The electron is repelled from the p-type material and attracted to the n-type material, moving to the n-type material and joining the other electrons in the region on the right of the figure. Similarly, the hole is repelled from the n-type region and attracted to the p-type region, and it joins the other holes on the left of the figure. Thus, the properties of the junction separate the electrons and the holes formed from incident electromagnetic radiation and reduce the probability that they will recombine. This movement of electrons and holes results in a net current flow across the junction, this electric current can be provided to an external device connected to the junction. This is the basis of operation for the *photodiode*, or *photovoltaic cell*. The spatial extent of the photosensitive region can be increased by creating the equivalent of a large depletion region (i.e., charge carrier–free region) by sandwiching an intrinsic (pure) semiconducting layer between the p-type and n-type regions.

9.4 Application of Photovoltaic Devices

Because the operation of the photovoltaic cell requires that the photons that are incident on it have sufficient energy to produce electron-hole pairs, there is, as described, a maximum wavelength of light that produces this effect. The spectral response for some photovoltaic cells is illustrated in Figure 9.23. The cutoff at long wavelengths is due to the fact that the photon energy for longer wavelengths is less than the energy gap and is insufficient to create electron-hole pairs. Figure 8.1 shows that about 23% of the photons received from the sun do not have sufficient energy to be converted to electricity by a Si photovoltaic cell. In addition, much of the electromagnetic energy is converted into heat rather than electricity. The spectral response of a photovoltaic cell can be improved by utilizing a semiconducting material with a smaller energy gap, thus enabling more of the solar spectrum to be effective in producing electricity. This is seen in Figure 9.23 by the longer wavelength corresponding to the cutoff for germanium (E_g = 0.67 eV) compared with Si (E_g = 1.1 eV).

The maximum theoretical efficiency of photovoltaic cells based on different semiconducting materials is summarized in Table 9.2. Typical efficiencies for Si-based cells are around 15–17%, with higher quality cells giving up to about 23%. Techniques such as concentrating the light and splitting the light into different spectral components

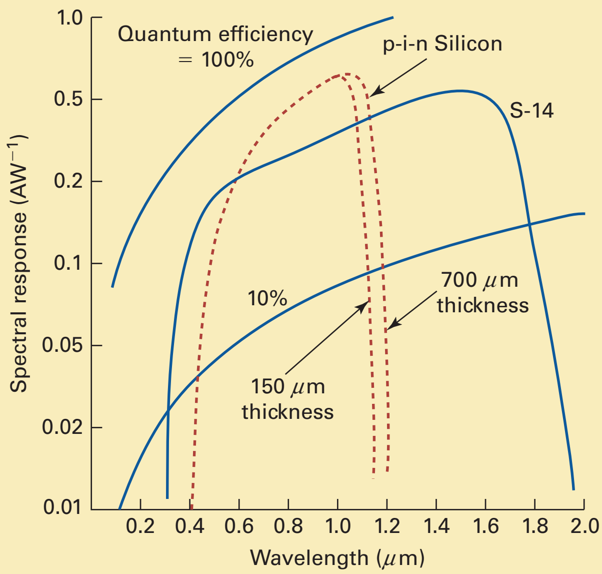


Figure 9.23: Spectral response of silicon (p-i-n Si)- and germanium (S-14)-based photovoltaic cells.

Based on RCA Solid State Division, Lancaster, Pennsylvania

Example 9.3

Calculate the cost per kWh averaged over an operational period of 10 years for a photovoltaic system with an installation cost of \$3.00 per W if the system operates with a capacity factor of 8% (this is the net result of the photovoltaic efficiency and the fraction of time that is daylight). (Do not include the cost recovery factor.)

Solution

Ten years correspond to (10 y) × (365 d/y) × (24 h/d) = 87,600 h. Over this time period, one watt of photovoltaic installation, operating at an 8% capacity factor, produces a total of

$$87{,}600 \text{ h} \times 0.08 \text{ W/W} = 7008 \text{ Wh/W} = 7.0 \text{ kWh/W}.$$

At a total cost of \$3.00 per W, this corresponds to

$$\frac{\$3.00/\text{W}}{7.0 \text{ kWh/W}} = \$0.43 \text{ per kWh}.$$

that are incident on cells with specific spectral responses have yielded efficiencies in excess of 40%.

Photovoltaic cells have been implemented on a variety of size scales. These may be considered in two different categories: off-grid and on-grid. These designations refer to systems that are not connected to the power utility grid and those that are, respectively.

Table 9.2: Energy gaps and maximum theoretical efficiency for solar radiation of some semiconducting materials for photovoltaic cell construction. Values are for room temperature. Some elemental components of these materials are toxic, such as arsenic and cadmium, and the world's resources of indium and gallium may be insufficient for large-scale use (Chapter 2).

material	E_g (eV)	maximum theoretical efficiency (%)
CdS	2.42	18
AlSb	1.6	27
CdTe	1.49	27
GaAs	1.43	26
InP	1.35	26
Si	1.11	25
Ge	0.67	13

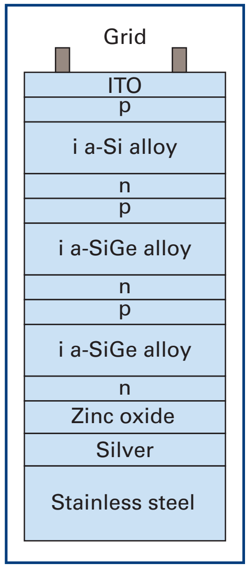
ENERGY EXTRA 9.2

Triple-junction photovoltaic cells

Most commercial photovoltaic cells have efficiencies for converting energy from solar radiation into electrical energy of 12–18%. A number of factors affect efficiency, but one of the most important is the spectral sensitivity of the semiconducting material used in the cell (Figure 9.23). The principle semiconductor property that governs the spectral response is the energy gap. Numerous semiconducting materials are known, and the energy gap (and hence the spectral response) of a material can be tuned by adjusting the composition of the material. The problem is that, if the energy gap is tuned to give the material a high efficiency for photons in the red end of the electromagnetic spectrum, then the efficiency at the blue end of the spectrum is sacrificed, and vice versa.

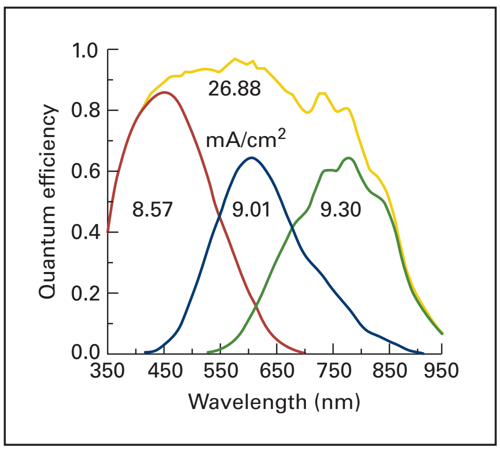
One approach to improving the efficiency of a photovoltaic cell over a broad spectral range is to make a sandwich (a multijunction) of materials that are sensitive over different portions of the spectrum. A triple junction consisting of one semiconducting material that is the most sensitive to the red photons, another that is the most sensitive to green photons, and a third that is the most sensitive to blue photons has been very successful in creating photovoltaic cells with overall high efficiencies to the solar spectrum.

An example of the triple-junction design is shown in the top right figure. In this example, the top layer is made of amorphous silicon (the designation "i a-Si" in the figure refers to a layer of intrinsic amorphous silicon sandwiched between layers of p-type and n-type silicon). The i a-Si layer has an energy gap of about 1.8 eV and is most sensitive to photons in the blue region of the solar spectrum. The middle layer is intrinsic amorphous silicon-germanium (i a-SiGe), with about 80% Si and 20% Ge (again sandwiched between p-type and n-type regions). This material has an energy gap of about 1.6 eV and is the most sensitive to photons in the green portion of the spectrum. The bottom layer is also i a-SiGe with about 60% Si and 40% Ge. This composition reduces the energy gap to about 1.4 eV and makes the material the most sensitive to red photons. The ordering of the layers is important because the top layer utilizes the highest-energy



S. Guha, "High-Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology" National Renewable Energy Laboratory, Report NREL/SR-520-26648 (1999)

Geometry of triple-junction photovoltaic cell.



S. Guha, "High-Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology" National Renewable Energy Laboratory, Report NREL/SR-520-26648 (1999)

Spectral responses of the three layers of a triple-junction and the total response.

Continued on page 317

Energy Extra 9.2 continued

photons and allows the lower-energy photons to propagate through to the layers beneath it, where they are utilized the most efficiently.

The bottom right figure on the previous page shows the spectral responses of the three layers; blue to red photons correspond to the horizontal axis from left to right in the figure. The total spectral response is illustrated by the total curve in the figure and shows a high efficiency over a wide range of photon energies (or wavelengths).

This approach has been successful in producing photovoltaic cells with overall efficiencies in the range of 40% (more than twice the efficiency of typical commercial silicon-based cells). Unfortunately, the cost of producing these cells, at least at the present, makes them economically viable only for specific applications. These applications include space vehicles, where weight is a more important consideration than cost, and devices where radiation is focused onto a small area and the solar cell size is small compared to the total collector area.

Topic for Discussion

If triple-junction photovoltaic (PV) devices could be produced at the same cost as simple Si-based devices, how would the cost of PV-generated electricity compare to wind, nuclear, and fossil fuels?

Off-grid photovoltaic cells typically fall into one of the following categories:

- Small units used to recharge batteries in portable electronic devices (Figure 9.11).
- Medium-sized units used for camping, emergency battery charging (Figure 9.24), portable road signs (Figure 9.25 on the next page), or power sources in remote areas (Figure 9.26 on the next page).
- Larger installations used for residential electric power (Figure 9.27 on the next page).

Individual cells are fairly small (typically less than about 10 cm on a side), but they can be combined in series (to increase voltage) and/or in parallel (to increase current). Individual cells can be rectangular (Figure 9.24) or circular (Figure 9.25).

The Solar Settlement in Freiberg, Germany (Figure 9.27) is a sustainable model community designed to produce net zero carbon emissions. Many of the homes, as seen in the figure, incorporate photovoltaic arrays to provide electricity.

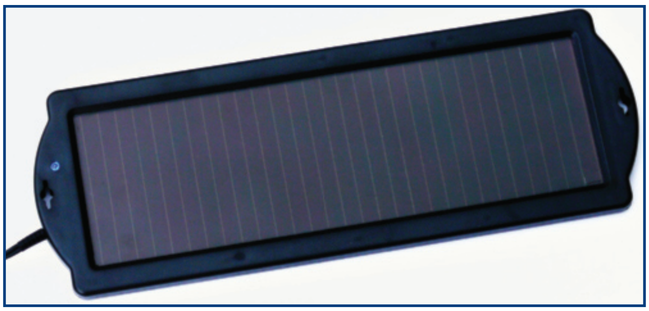


Figure 9.24: Portable 1.8-W_e solar panel. The dimensions of the active area are approximately 9 cm $\times$ 30 cm.

Richard A. Dunlap

Figure 9.25: Portable road sign at construction site that utilizes a photovoltaic array (about 1 m × 2.5 m) to charge batteries.

Richard A. Dunlap

Figure 9.26: Photovoltaic array for providing power at a remote radio transmitter station.

Richard A. Dunlap

Figure 9.27: Photovoltaic solar panels on homes in the ecological Vauban district in Freiburg, Baden-Wuerttemberg, Germany.

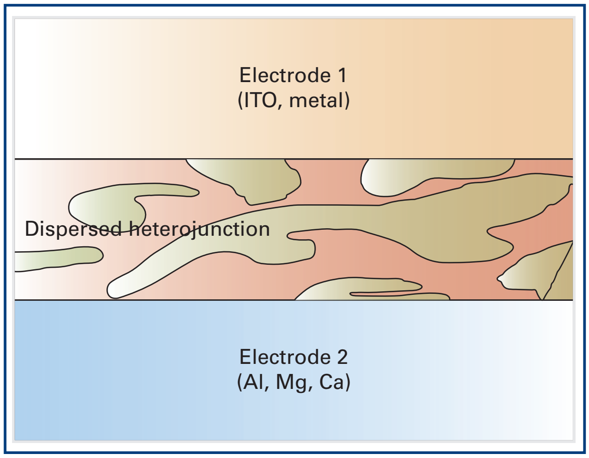
imageBROKER/Alamy Stock Photo

ENERGY EXTRA 9.3

Dye-sensitized solar cells

Clearly, the major problem with electricity generated by photovoltaic devices is the cost per kWh. One approach to dealing with this difficulty is to produce photovoltaic cells with higher efficiency. This, of course, has the advantage that the power generated per unit land area is greater. However, because more efficient photovoltaic cells are more expensive, this is not an obviously viable trade-off between productivity and price. The opposite approach is to design cells that are as inexpensive as possible without being so concerned with efficiency, thus taking a different approach to photovoltaic materials and photocell design. Dye-sensitized solar cells (DSSCs) are a type of organic photovoltaic cell that has attracted considerable interest in recent years. These cells utilize a very different method of cell construction and manufacture that may lead to innovative and practical devices.

A traditional photovoltaic cell consists of a sandwich of an n-type material and a p-type material between two conducting electrodes. When a photon of sufficient energy (i.e., greater than the energy gap) enters into the region near the semiconducting junction, an electron-hole pair can be formed, resulting in a current through an external circuit. The geometry is somewhat limited because the electron and hole must reach the electrode before recombining. However, the photosensitive region can be made larger and, in principle, more economical, by using the heterojunction design. In a heterojunction device, the semiconducting region consists of a mixture of different materials as shown in the following figure. In a DSSC, the heterojunction is based on a piece of nonporous TiO_2. TiO_2 has a relatively poor efficiency for creating electron-hole pairs in response to photons because of its large energy gap. However, the pores in TiO_2 are filled with a very photosensitive organic dye. The top electrode is often made of a halide-doped tin oxide that is both optically transparent and conducting. This forms the

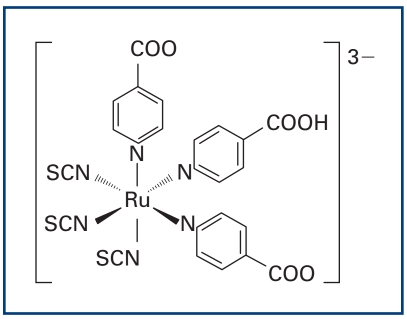


Based on University of Minnesota, Organic Photovoltaic Solar Cells using Graded Heterojunction Technology, http://www.license.umn.edu/Products/Organic-Photovoltaic-Solar-Cells-using-Graded-Heterojunction-Technology__Z09174.aspx

Schematic of dispersed heterojunction photovoltaic cell.

electrical connection to the cell and allows light to enter into the photosensitive region. If the size of the dispersed grains in the heterojunction is comparable to the charge carrier diffusion length, then the charges formed in response to a photon have a good chance of reaching a semiconducting interface before recombination takes place.

The earliest DSSCs produced in the mid-1990s were primarily sensitive only to the high-energy (UV) part of the solar spectrum. In recent years, materials (dyes) that are sensitive to the entire optical spectrum have been developed. Because these materials are effective at absorbing all optical wavelengths,



Ph0987

Structure of triscarboxy-ruthenium terpyridine (black dye).

Continued on page 320

Energy Extra 9.3 continued

they appear black and are thus referred to as *black dyes*. The most common black dyes are based on organic ruthenium-containing complexes as shown in the figure on the previous page at bottom right.

DSSCs have been produced with efficiencies in the range of 11%. This is less than the efficiency for traditional Si-based semiconducting photovoltaic cells, which can be close to 20% efficient, and the element ruthenium is expensive. However, the hope is that new, economically viable materials (that do not include ruthenium) may be developed and that this approach to photovoltaic cell design may yield devices that are competitive in terms of cost per kW/m^2.

Topic for Discussion

The problem of the cost and availability of materials is prevalent when dealing with the development of new technologies. The use of ruthenium in DSSCs is only one example of a great need to develop new materials that have competitive properties but that are less expensive and more readily available. Find information about the market value of ruthenium and the quantity produced each year. An excellent website dealing with elemental resources that has useful information and links is http://minerals.usgs.gov/minerals/pubs/commodity/. Discuss the importance of considering how science, technology, and economics must all play a role in designing our future.

Experimental automobiles (Figure 9.28) and even airplanes (Figure 9.29) that are powered by photovoltaic cells have been constructed. Although these vehicles are interesting engineering challenges, the power density in sunlight is insufficient to make them practical.

On-grid photovoltaic facilities exist in a number of countries and provide electric power for distribution through the power grid. A typical system for integrating a photoelectric array with the power grid is illustrated in Figure 9.30. The thermal generator (i.e., coal or nuclear generating facility) provides the primary AC power to the grid. DC power from the photovoltaic array is stored in a battery system. DC power from the photovoltaic array and from the battery storage system is converted to AC by the inverter. Voltage is matched to the grid power from the thermal generator by a step-up transformer. The synchronizing breaker connects the power from the photovoltaic array to the grid when the voltages are matched in frequency, amplitude, and phase.

Typically, large photovoltaic facilities have rated capacities of hundreds of MW_e (see Figure 9.12). At present the world's largest photovoltaic facility is the 850 MW_e

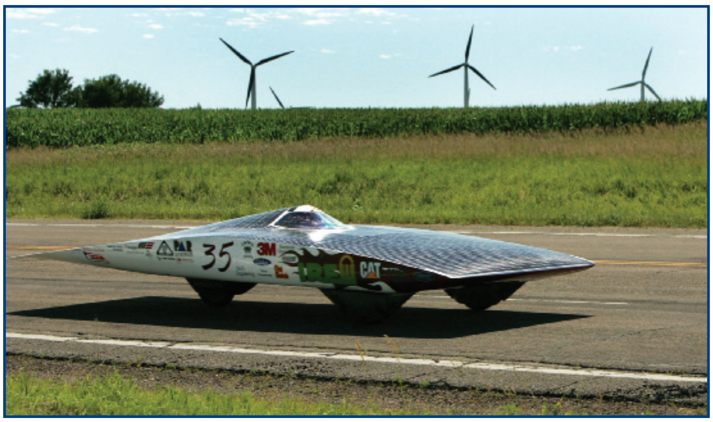


Figure 9.28: Photovoltaic-powered automobile.

Stefano Paltera, the NASC's official photographer

Figure 9.29: Photovoltaic-powered airplane.

NASA photo by Nick Galante/PMRF

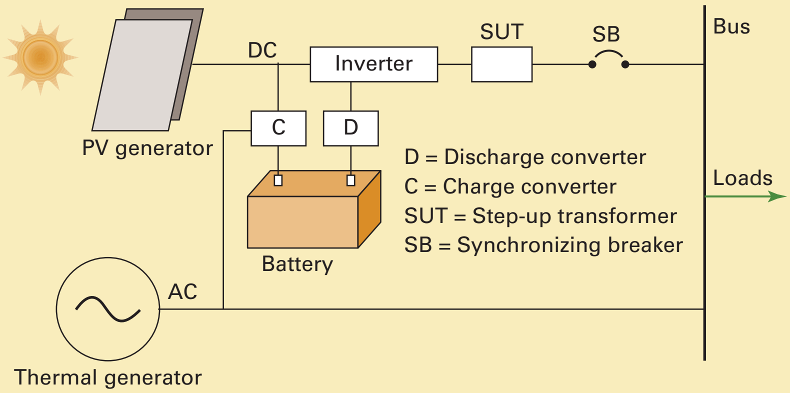


Figure 9.30: A grid-connected photovoltaic system.

Based on M.R. Patel, Wind and Solar Power Systems: Design, Analysis, and Operation (2nd ed.), CRC Press, Taylor & Francis, Boca Raton (2006)

Longyangxia Dam Solar Park in Gonghe, Qinghai, China. This facility was constructed in two phases, with an initial 320 MW_e installation completed in 2013 and an additional 530 MW_e installation completed in 2015. The largest photovoltaic generating station in the United States is presently the Solar Star Power Plant in California, completed in 2015 with a rated capacity of 579 MW_e (see Figure 9.31 on the next page).

The cost of photovoltaics has decreased considerably in recent years, as Figure 9.32 on the page 323 shows. These values are for the cost per watt of photovoltaic cell, and it should be noted that the cost for a complete installation would also include a suitable electrical storage method (i.e., batteries) and appropriate electronics (e.g., inverters) as discussed later in the present chapter.

Example 9.4

Using the average (cloud-free) insolation on earth (Chapter 8), calculate the area of a horizontal photovoltaic array with an efficiency of 20% that would be needed to satisfy the residential electric needs of a city of 250,000 people with an average of 2.6 people per household.

Solution

This city would consist of $250{,}000/2.6 = 9.6 \times 10^4$ homes. Based on the discussion in Chapter 2, we estimate the average power requirement per home as 1370 W. The total requirement for the city would be

$$(9.6 \times 10^4) \times (1370\ \text{W}) = 1.32 \times 10^8\ \text{W}.$$

The average cloud-free insolation averaged over the year and at all locations on earth is (from Chapter 8) 168 W/m^2. Thus the city's electrical needs would require (at a 20% efficiency)

$$\frac{1.32 \times 10^8\ \text{W}}{0.2 \times 168\ \text{W/m}^2} = 3.9 \times 10^6\ \text{m}^2,$$

or a square array about 2 km on a side.

The cost of photovoltaics may be viewed as primarily a capital cost with little or no operating costs compared with, for example, coal power, which requires a continuous supply of fuel. However, the capital costs of a photovoltaic system must be amortized over its expected lifetime to determine the actual cost per unit energy (Chapter 2). The life expectancy of a photovoltaic cell is probably about 20 years, although the life expectancy for the batteries in the storage system might be less. Table 9.3 summarizes the

Figure 9.31: Solar photovoltaic panels at the 579 MW$_e$ Solar Star Power Plant in Los Angeles County, California. In contrast to most other large photovoltaic power stations, Solar Star uses single-axis tracking collectors rather than fixed collectors.

Daniel Schweinert/Shutterstock.com

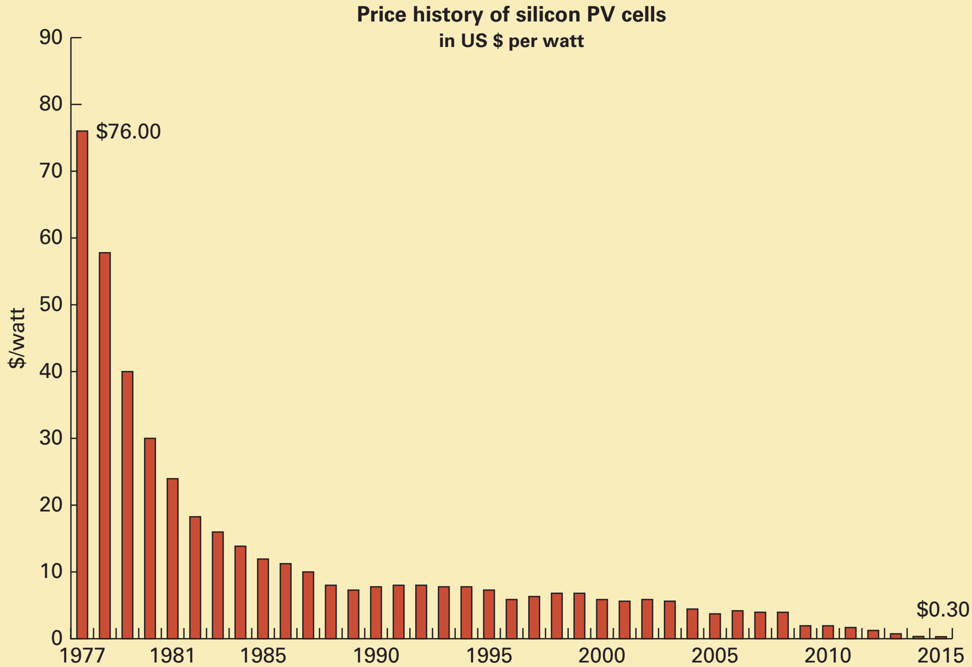


Figure 9.32: Cost per W_e for crystalline silicon photovoltaic cells 1977 to 2015.

Based on data: 1977–2013: Bloomberg, New Energy Finance, (archived) 2014: based on average sales price of $0.36/watt on 6 June 2014 from EnergyTrend.com 2015: based on average sales price of $0.30/W on 29 April 2015 from EnergyTrend.com

Table 9.3: Projected cost per MWh generated for utility scale generating stations entering service in 2022. Government subsidies are not included in the estimates.

technology	US$/MWh
solar-thermal	235.9
wind-offshore	158.1
advanced coal	139.5
natural gas combustion turbine	110.8
nuclear	102.8
solar-photovoltaic	84.7
hydroelectric	67.8
wind-onshore	64.5
natural gas-combined cycle	58.1
geothermal	45.0

Data adapted from U.S. Energy Information Administration, http://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf estimated cost per unit energy for photovoltaics compared with other energy production methods. These estimates from the United States Energy Information Administration represent the estimated cost per MWh generated by stations entering service in the United States in 2022. The unusually high value for electricity produced from coal (compared to the low value for currently operating power stations) results from the inclusion of 30% carbon sequestration. The table indicates that photovoltaics are expected to compete favorably with other energy technologies in the relatively near future.

9.5 Global Use of Photovoltaics

Installed photovoltaic capacity has increased dramatically worldwide in recent years, as Figure 9.33 illustrates. This increase resulted from increasing concern over diminishing fossil fuel resources and their environmental impact, coupled with the decreasing cost of photovoltaic cells (Table 9.3). On the basis of current trends, growth of photovoltaic capacity is expected to continue. Table 9.4 summarizes the total installed capacity of the countries with more than 2 GW_e photovoltaic capacity. China and Japan have seen the greatest growth in absolute terms in recent years. However, Germany has maintained the greatest per-capita capacity in recent years.

The longevity of sunlight as an energy source is, for all practical purposes, infinite, but it is necessary to consider its availability. From equation (8.2), the total insolation on the outside of the atmosphere of the earth is 1.8×10^{17} W. On average, about half of this is transmitted through the atmosphere, giving a total insolation at the surface of 9×10^{16} W. Considering a modest photovoltaic efficiency of 15%, this gives the potential for 1.3×10^{16} W_e from photovoltaic generation worldwide. In the Preface, it was seen that the total primary energy use worldwide is 6.0×10^{20} J per year for an average power

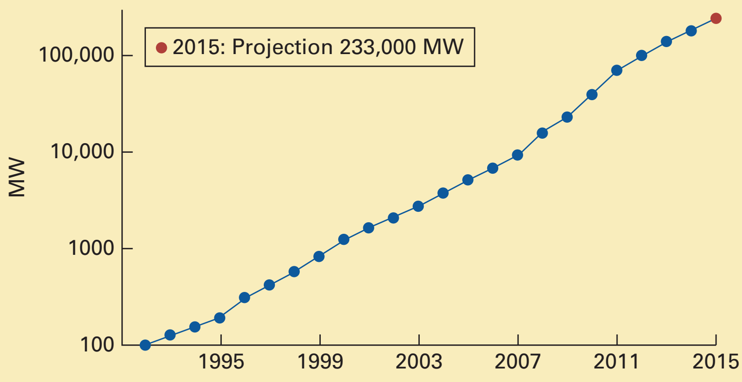


Figure 9.33: Cumulative installed world photovoltaic capacity as a function of year since 1992. Note the logarithmic vertical scale.

Based on data from: 1992-1995: Wikipedia article growth of photovoltaics–collected figures of 16 main markets, including Australia, Canada, Japan, Korea, Mexico, Western European countries, and the United States. 1996–1999: BP-Statistical Review of world energy, 2014 (XLS-spread-sheet). 2000–2013: SPE (former EPIA) Global Market Outlook for Photovoltaics (Report, June 2014, archived). 2014: Snapshot of Global PV 1992–2014 (archive) and IHS estimates/projections for worldwide deployment in 2014 and 2015 (March 2015). 2015 (projection only). Averaged from several different forecasting groups, companies and organizations. Data listed in article Growth of photovoltaics

Table 9.4: Total photovoltaic capacity and capacity per capita as of 2015 for countries with greater than 2 GW_e capacity.

country	total capacity (MW_e)	population (10^6)	capacity per capita (W_e)
China	43,530	1376.0	31.6
Germany	39,700	80.7	491.9
Japan	34,410	126.6	271.8
United States	25,620	321.8	79.6
Italy	18,920	59.8	316.4
United Kingdom	8780	64.7	135.7
France	6580	64.4	102.2
Spain	5400	46.1	117.1
Australia	5070	24.0	211.3
India	5050	1311.1	3.9
South Korea	3430	49.8	68.9
Belgium	3250	11.3	287.6
Greece	2613	11.0	237.5
Canada	2500	35.9	69.6
Czech Republic	2083	10.8	192.9

consumption of $(6.0 \times 10^{20}\ \text{J/y})/(3.156 \times 10^{7}\ \text{s/y}) = 1.9 \times 10^{13}$ W. Thus, the utilization of only about 0.15% of the available solar energy would fulfill all of our energy needs. Certainly, the use of photovoltaic arrays would be impractical or uneconomical at some locations on earth. Terrestrial locations would probably be more practical than most of the oceans, while northern or southern latitudes would provide very low efficiency. The fraction of land area necessary for solar energy to provide all energy needs can be considered on a country-by-country basis. Population density and per-capita energy use, as well as latitude and climate conditions, would be the relevant factors. A comparison between the United States and Canada can be considered as an example, and a summary of this analysis is given in Table 9.5. The insolation for the United States shown in Figure 8.2 has a typical value of about 200 W/m^2. For Canada, it is assumed that solar collectors would be located in fairly southern areas where the average insolation is in the range of about 150 W/m^2. The table shows that a relatively small amount of the land area of the United States and Canada would need to be dedicated to the production of electricity by solar photovoltaics in order

Table 9.5: Factors determining the fraction of land area needed to provide all primary energy needs by the use of photovoltaics in Canada and the United States. Photovoltaic efficiency of 15% has been assumed.

country	total annual energy use (J)	average power consumption (W)	typical insolation (W/m^2)	land area needed (km^2)	total land area (km^2)	% land area needed
United States	1.0×10^{20}	3.2×10^{12}	200	1.1×10^{5}	9.63×10^{6}	1.1
Canada	1.3×10^{19}	4.1×10^{11}	150	1.8×10^{4}	9.98×10^{6}	0.18

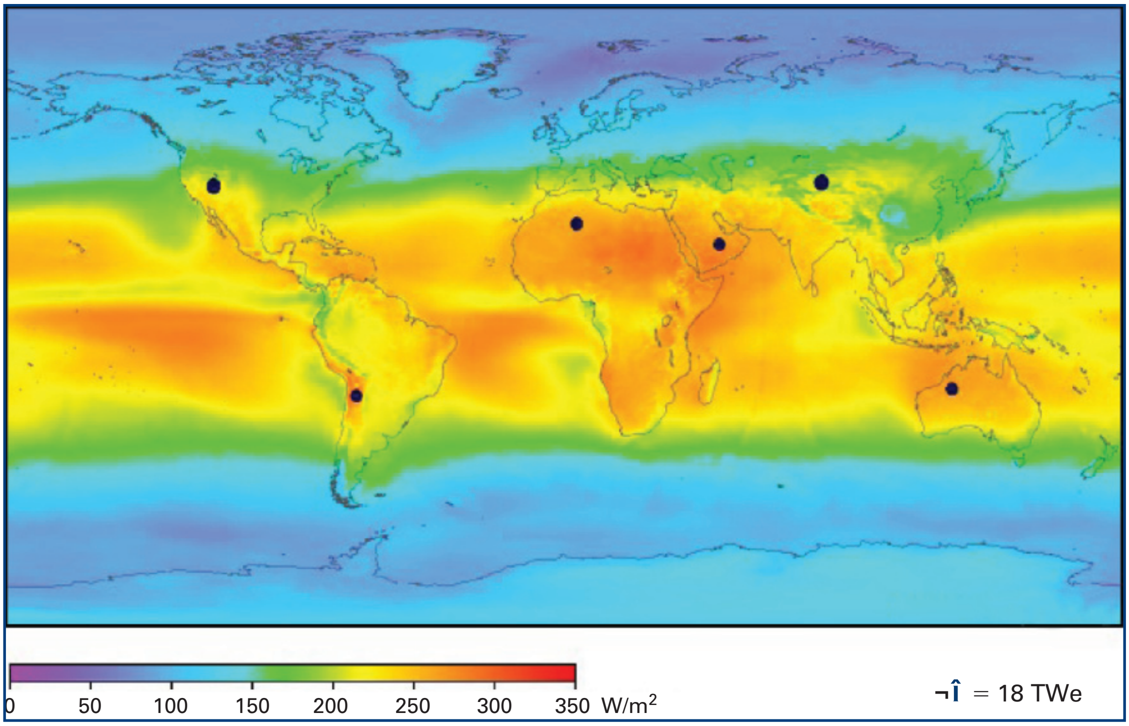


Figure 9.34: Land area needed to supply the world's energy needs from solar. Average insolation is illustrated.

Matthais Loster, http://www.ez2c.de/ml

to satisfy all primary energy requirements. For the United States, a square about 300 km on a side would be required; that is an area about the size of Ohio. For Canada, a square about 135 km on a side (about one third the area of Nova Scotia) would be required. A number of smaller facilities with an equivalent total area would likely be more practical than a single large facility. About six 300 km $\times$ 300 km facilities located worldwide in relatively sunny, low-population-density areas as shown in Figure 9.34 (or a comparable number of smaller facilities), would satisfy all of the world's energy needs.

Solar energy is the only single-energy resource that has the capability to provide enough energy to fulfill all of our needs and that is indefinitely renewable. The technology for doing this is within our means but would require that we adapt our energy infrastructure for the exclusive use of electricity as an energy source. The continued availability of (relatively) inexpensive fossil fuels does not provide the financial incentive for this development.

9.6 Summary

Solar radiation is the only source of nonfossil fuel energy that is plentiful enough to fulfill all of society's energy requirements, both for the present and for the foreseeable future. Although the direct use of solar energy for applications such as space heating contribute to energy needs on a residential heating scale, it is the production of electricity from solar radiation, as described in this chapter, for distribution over the grid, that has the potential to satisfy the bulk of our energy requirements in the future. The ways in which solar energy can be used to generate electricity were described. There are basically two approaches: heat engines and photovoltaics. This chapter discussed systems for focusing sunlight onto a small area where it is used to heat a working fluid. The fluid is then used to run a heat engine to produce mechanical energy, which then generates electricity by means of a generator. Experimental facilities use one of three geometries: parabolic troughs, parabolic reflectors, or central receivers. The efficiency of these devices is ultimately limited by the Carnot efficiency.

This chapter provides an introduction to the basic semiconductor physics needed to describe the operation of a photovoltaic device. Both n-type and p-type semiconducting materials are formed by the inclusion of donor or acceptor impurities in a host material. These materials have either an excess electron in the conduction band or an excess hole in the valence band, respectively. A junction between an n-type and a p-type material is sensitive to solar energy and constitutes the basic design of a photovoltaic cell. Photons incident on the junction produce electron-hole pairs that provide a current through an external circuit, thus providing usable electrical energy.

Different semiconducting materials are sensitive to different regions of the electromagnetic spectrum, and this is a major factor in limiting the efficiency of photovoltaic devices. There is a trade-off between efficiency and economy. High-efficiency devices can have efficiencies of about 40% for conversion of solar energy to electrical energy, but they are expensive. More economical devices have efficiencies of about 18%.

Although the photovoltaic installations themselves would seem to be environmentally neutral, the overall environmental concerns of solar electricity are complex. The manufacturing processes needed to produce photovoltaic materials are intensive (per installed watt power capability) because the energy density of sunlight is low, and these processes must be included in an overall evaluation of environmental impact. Some elements used in photovoltaic cells are toxic, and some, such as indium, are of limited worldwide availability. All of these factors contribute to the present high cost of solar electricity, have possible implications for future developments, and must be considered in any overall analysis of the viability of photovoltaics. However, solar photovoltaics are still an attractive alternative to diminishing fossil fuel supplies, and there has been a substantial increase in their use in recent years. Germany has a very ambitious development program in this area and has been the leader in implementing this technology for providing electricity to the grid. The development of photovoltaic cells with good efficiency that can be manufactured economically using low–cost, nontoxic components is an area of active research, and the future availability of such materials would benefit the growth of this renewable energy resource.

Problems

9-1 Consider a 1-m-wide parabolic trough reflector with a 1-cm-inside-diameter pipe filled with oil at its focus. If all of the solar radiation is converted into heat, estimate the time required at midday on a sunny day to raise the temperature of the oil from 20ºC to 100ºC.

9-2 Assume that all of our energy is obtained from solar by means of photovoltaic devices with an efficiency of 18% using horizontal panels. If all energy is produced in the United States on a state-by-state basis, calculate the percent of land area needed to supply energy in Rhode Island and Idaho. Use an average annual per-capita energy requirement of 350 GJ. Comment on the suitability of this approach.

9-3 A house at 40ºN latitude has a roof of dimensions 8 m by 15 m. This area is covered with photovoltaic panels at the optimal fixed angle with an efficiency of 17%. Assuming average sky conditions, what is the annual energy production from this installation? If this electricity were generated by a coal-fired thermal plant operating at 38% efficiency, how much coal would be needed? On the basis of this comparison, what is the annual reduction (in kilograms) of CO_2 that results from this use of photovoltaics?

9-4 If all of the energy for humanity is generated using horizontal solar photovoltaic arrays with an efficiency of 15% and which occupy 1% of the land area of the earth, what is the maximum population density that can be supported?

9-5 Estimate the diameter of a mirror array associated with a solar power tower, as illustrated in Figure 9.6, that would replace a 1-GW_e coal-fired generating station. Be sure to consider the method by which electricity is generated, as illustrated in Figure 9.8. Discuss the practicality of such a design. Consider the relationship between the height of the central tower and the arrangement of mirrors near the outer portions of the array. Each mirror must have a clear view of the central receiver that is not obscured by the mirror in front of it. Does this place a restriction on the size of the array in the context of the tower height?

9-6 What is the maximum wavelength of light (in nanometers) that would produce an output from a photovoltaic device manufactured from a semiconductor with an energy gap of 1.02 eV?

9-7 What is the maximum wavelength of the light that produces voltage in a CdS photovoltaic device? Discuss this in terms of the spectrum of sunlight as presented in Chapter 8.

9-8 Consider a typical family vehicle powered by photovoltaics, similar to the vehicle shown in Figure 9.28, where the top surface is covered with 20% efficient cells. Compare the power available in such a vehicle on a sunny day in comparison with a typical gasoline-powered vehicle. Some typical vehicle characteristics are given in Table 19.5.

9-9 A metal plate is placed on a horizontal surface on a sunny day when the solar insolation is 500 W/m^2. Calculate its equilibrium temperature as a function of its emissivity, and make a plot of these results for values of the emissivity from $\varepsilon = 0.1$ to $\varepsilon = 1.0$.

9-10 If the focal area in Example 9.1 is made of a material with an emissivity of 0.9 and this loses heat only by radiation from the 5-cm-diameter area, calculate its equilibrium temperature.

9-11 Calculate the energy of an electron in the 1s energy level in a hydrogen atom.

9-12 What is the maximum frequency of light that will produce an output from a Ge-based photovoltaic cell?

9-13 The northern part of the United States, as Figure 8.2 shows, has a yearly 24-hour average solar insolation that is typical of the average value worldwide. Using this worldwide average, consider the economics of a photovoltaic installation. If the photovoltaic efficiency is 20% and a payback period of 3 years is expected (exclusive of the cost recovery factor), what is the maximum acceptable installation cost per W? Assume electricity costs $0.10 per kWh.

9-14 Compare the photovoltaic capacity for the United States given in Table 9.4 with the energy use shown in Figure 2.5. Comment on these results.

9-15 Using the energy of electrons in a hydrogen atom as a function of *n*, as given by equation (9.1), and following along the lines of the graph in Figure 9.13, determine all combinations of values of *n* for which electronic transitions will produce optical photons.

9-16 Water flows through a 5-cm-diameter pipe at the focus of a 2-m-wide parabolic trough reflector that is 5 m long at a rate of 0.2 L/s. If the insolation is 500 W/m^2 and all of the solar energy is converted into heat, what is the increase in the temperature of the water after it has traversed the length of the reflector?

9-17 A 15-m-diameter parabolic dish utilizes a Stirling engine for electricity generation. On a sunny day the dish receives an insolation that is 47% of the value of the solar constant. Estimate its output in W_e.

9-18 For a photovoltaic efficiency of 20% and an average peak insolation of 350 W/m^2, calculate the additional number of km^2 of solar collectors that would need to be installed in the United States to equal the per-capita photovoltaic capacity of Germany.

9-19 A photovoltaic panel with an efficiency of 19% receives an average insolation equal to the average worldwide average insolation on a horizontal surface. This panel is used with an appropriate storage system (100% efficient) to meet the average household electricity requirements (no electric heat) presented in Chapter 2.

(a) What is the required area of the panel?

(b) What is the annual savings in CO_2 emissions compared to the same amount of electricity supplied by 40% efficient coal-fired generating stations?

9-20 Assume that the portable solar panel shown in Figure 9.25 has an efficiency of 19%.

(a) What is the insolation needed to provide the rated output power?

(b) A camper connects this panel, in sunlight according to part (a), to an immersion heater in a 1-L container of water. How long will it take to increase the temperature of the water from 15°C to 100°C (without boiling)? Assume there is no heat loss.

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