Fundamentals of Renewable Energy

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CHAPTER 4

Solar Energy Applications

INTRODUCTION

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Advantages

- **Free and nonpolluting**

Disadvantages

- **The rate of solar radiation on a unit surface is quite low, so solar collectors with large surface areas are installed**
- **costly and requires a lot of space**
- **available in reasonable quantities only in certain locations of the world and certain seasons of the year and times of the day**

INTRODUCTION

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Storage of solar energy for nighttime use is an option to tackle noncontinuous feature of solar energy but this adds to system cost and it may not be effective in many applications. Nonetheless, we should try to get the best out of solar energy by utilizing the most current technologies and continue to work on improving the solar systems and making them more cost-effective.

INTRODUCTION

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The conversion of solar energy

- Heliochemical process
- Heliothermal process
- Helioelectrical process

FLAT-PLATE SOLAR COLLECTOR

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- ✓ Produce useful heat from solar energy
- ✓ Produce hot water used in residential and commercial buildings
- ✓ Used for space heating
- ✓ They are very common in southern Europe and Asia
- ✓ A complete unit that provides hot water needs of a family house costs as little as $1000 or less in some parts of the world

Figure 4-1
Solar water collectors on the roof of residential buildings.

FLAT-PLATE SOLAR COLLECTOR

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An active, closed loop solar water heater uses a pump for the circulation of water containing antifreeze fluid.

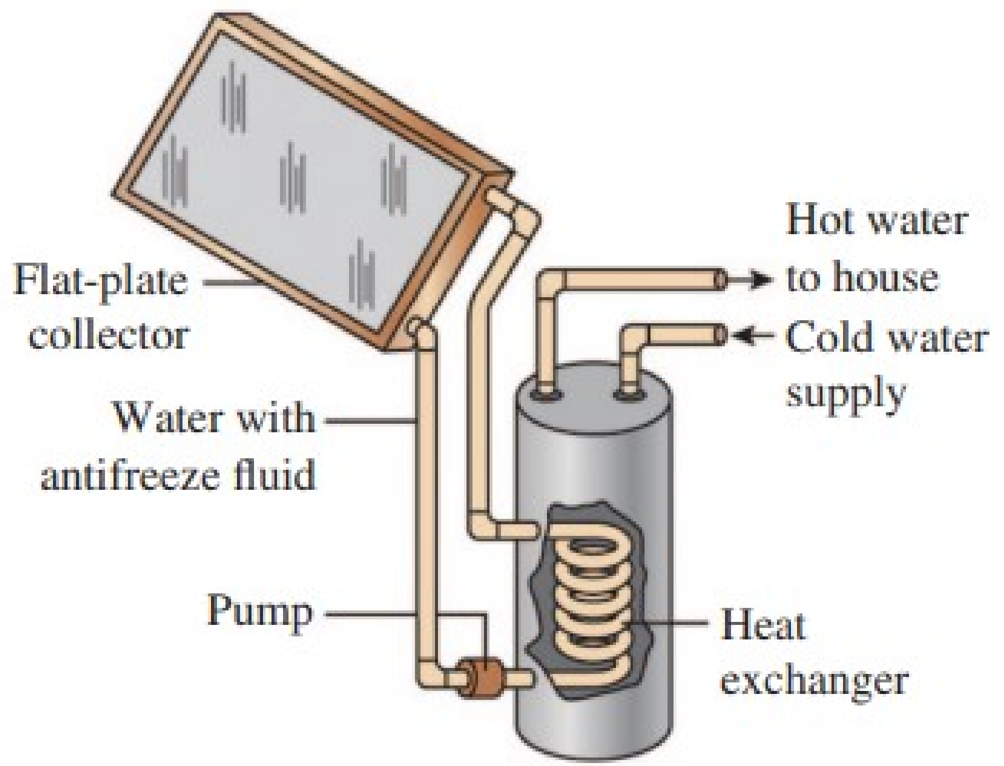

Figure 4-2
An active, closed loop solar water heater.

FLAT-PLATE SOLAR COLLECTOR

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The rate of solar heat absorbed by the absorber plate is

$$\dot{Q}_{abs} \quad \tau\alpha A G$$

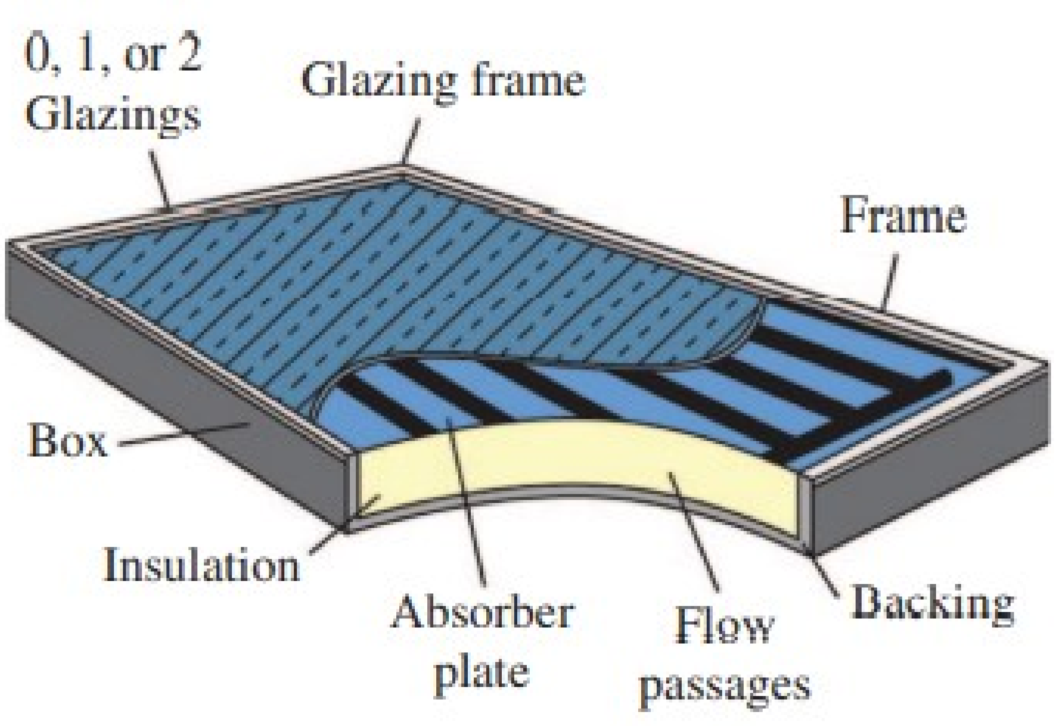

Figure 4-3
The cutaway view of a flat-plate solar collector.

FLAT-PLATE SOLAR COLLECTOR

There is heat loss from the collector by convection to the surrounding air and by radiation to surrounding surfaces and sky. The rate of heat loss can be expressed as

$$\dot{Q}_{loss} = UA(T_c - T_a)$$

The useful heat transferred to the water is the differrence between the heat absorbed and the heat lost:

$$\dot{Q}_{useful} = \dot{Q}_{abs} - \dot{Q}_{loss} = \tau\alpha A G - UA(T_c - T_a)$$

the useful heat can also be determined from

$$\dot{Q}_{useful} = \dot{m} c_p (T_{w,out} - T_{w,in})$$

FLAT-PLATE SOLAR COLLECTOR

The efficiency of a solar collector may be defined as the ratio of the useful heat delivered to the water to the radiation incident on the collector:

$$\eta_c = \frac{\dot{Q}_{useful}}{\dot{Q}_{incident}} = \frac{\tau\alpha AG - UA(T_c - T_a)}{AG} = \tau\alpha - U\frac{(T_c - T_a)}{G}$$

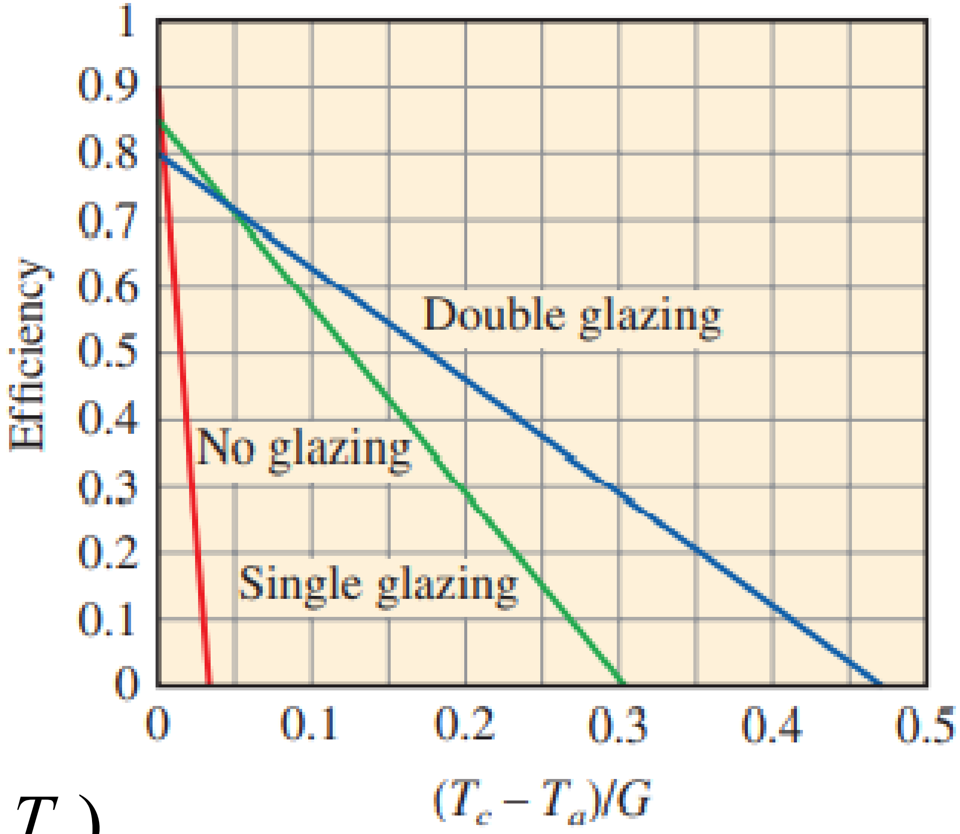

Figure 4-4
Collector efficiency for three different collectors.

FLAT-PLATE SOLAR COLLECTOR

The collector efficiency may be defined as a function of water inlet temperature as

$$\eta_c = F_R \tau\alpha - F_R U \frac{(T_{w,in} - T_a)}{G}$$

The solar collector is normally fixed in position. As the angle of solar incident radiation changes throughout the day, the product ta also changes. This change can be accounted for by including an incident angle modifier as:

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{(T_{w,in} - T_a)}{G}$$

EXAMPLE 4-1 The specifications of two flat-plate collectors are given as follows:

Single glazing: τ= 0.96, α= 0.96, U = 9 W/m2· °C

Double glazing: τ= 0.93, α= 0.93, U = 6.5 W/m2· °C

The heat removal factor for both collectors is 0.95, the solar insolation is 550 W/m2, and the ambient air temperature is 23°C. For each collector, determine (a) the collector efficiency when the water enters the collector at 45°C, (b) the temperature of water at which the collector efficiency is zero, and (c) the maximum collector efficiency. Take the incident angle modifier to be 1. (d) Also, plot the collector efficiency as a function of $\frac{(T_c - T_a)}{G}$ for each collector.

Solution (a) The collector efficiency is determined from Eq. (4-7) for each collector to be Single glazing:

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{(T_{w,in} - T_a)}{G}$$

$$= 0.95 \times 1 \times 0.96 \times 0.96 - 0.95 \times 9 (W/m^2.^oC) \frac{45^oC - 23^oC}{550 W/m^2}$$

$$= 0.534$$

Double glazing:

$$\eta_c = F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{(T_{w,in} - T_a)}{G}$$

$$= 0.95 \times 1 \times 0.93 \times 0.93 - 0.95 \times 6.5 (W/m^2.^oC) \frac{45^oC - 23^oC}{550 W/m^2}$$

$$= 0.575$$

(b) Setting the collector efficiency zero in Eq. (4-7) gives

Single glazing:

$$F_R K_{\tau\alpha} \tau\alpha - F_R U \frac{(T_{w,in} - T_a)}{G} = 0$$

$$0.95 \times 1 \times 0.96 \times 0.96 = 0.95 \times 9 (W/m^2.^oC) \frac{T_{w,in} - 23^oC}{550 W/m^2}$$

$$T_{w,in} = 79.3^oC$$

Double glazing:

$$F_R K_{\tau\alpha} \tau\alpha = F_R U \frac{(T_{w,in} - T_a)}{G}$$

$$= 0.95 \times 1 \times 0.93 \times 0.93 = 0.95 \times 6.5 (W/m^2.^oC) \frac{T_{w,in} - 23^oC}{550 W/m^2}$$

$$T_{w,in} = 96.2^oC$$

(c) The collector efficiency is maximum when the water temperature is equal to air temperature. Then,

Collector A:

$$\eta_{c,\max} = F_R K_{\tau\alpha} \tau\alpha = (0.95)(1)(0.96)(0.96) = 0.876$$

Collector B:

$$\eta_{c,\max} = F_R K_{\tau\alpha} \tau\alpha = (0.95)(1)(0.93)(0.93) = 0.822$$

(d) We plot the collector efficiency as a function of $(T_c - T_a)/G$ for each collector, as shown in Fig. 4-5.

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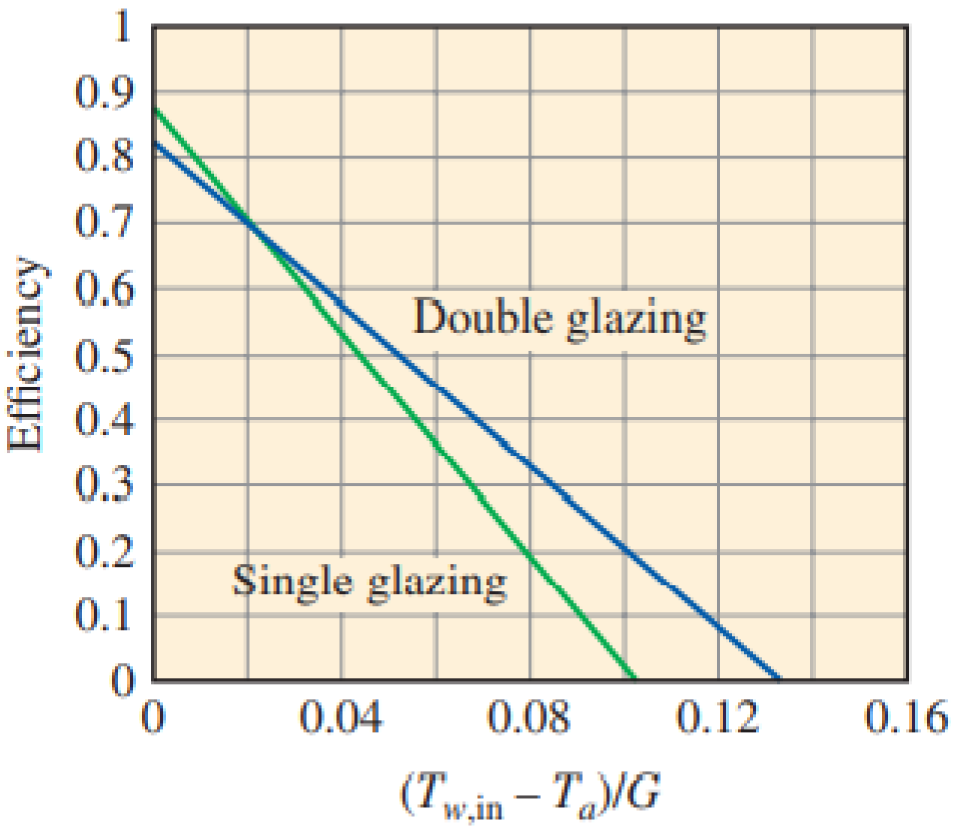

Figure 4-5
Collector efficiency for the two collectors considered in Example 4-1.

EXAMPLE 4-2 A solar collector provides the hot water needs of a family for a period of 7 months except for 5 months of winter season. The collector supplies hot water at an average temperature of 55°C and the average temperature of cold water is 18°C. An examination of water bills indicates that the family uses an average of 15 tons of hot water from the solar collector per month. An electrical resistance heater supplies hot water in winter months. The cost of electricity is $0.13/kWh and the efficiency of the electric heater can be taken to be 93 percent considering heat losses from the system. Determine the annual electricity and cost savings to this family due to solar collector.

Solution (a) The specific heat of water at room temperature is cp = 4.18 kJ/kg · °C. The amount of solar water heating during a month period is

$$Q = mc_p(T_1 - T_2) = (15{,}000 kg / month)(4.18 kJ / kg.^oC)(55 - 18)^oC$$

$$= 2.32 \times 10^6 kJ / month$$

The amount of gas that would be consumed (or saved) during the 7-month period is

$$Electricity\ \text{savings} = \frac{Q}{\eta_{heater}} = (7 months)\frac{2.320 \times 10^6\ \text{kJ/month}}{0.93}\left(\frac{1\ \text{kWh}}{3600\ \text{kJ}}\right) = 4850\ \text{kWh}$$

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The corresponding cost savings is

$$\text{Cost savings} = \text{Electricity savings} \times \text{Unit cost of electricity}$$
$$= (4850\,\text{kWh})(\$0.13/\text{kWh})$$
$$= \$631$$

CONCENTRATING SOLAR COLLECTOR

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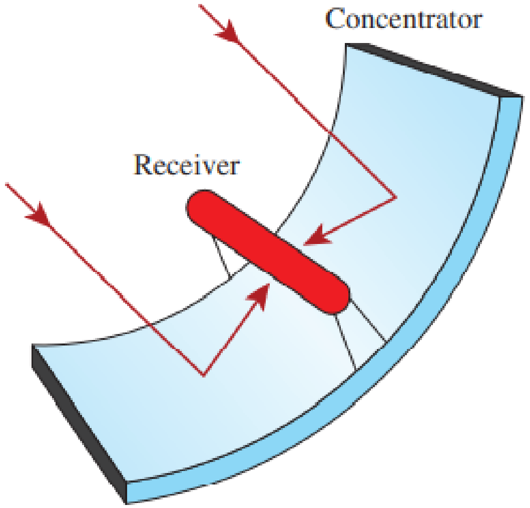
Hot fluid at much higher temperatures can be produced using concentrating collectors by concentrating solar radiation on a smaller area.

In a concentrating collector, solar radiation is incident on the collector surface, called aperture area Aa, and this radiation reflected or redirected into a smaller receiver area Ar. The concentration factor CR is defined as

$$CR = \frac{A_a}{A_r}$$



(a)

(b)

Figure 4-6
Parabolic trough collector. (a) Schematic diagram. (b) Photo.

CONCENTRATING SOLAR COLLECTOR

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The net rate of solar radiation supplied to the receiver is

$$\dot{Q}_r = \eta_{ar} A_a G$$

The rate of heat loss from the collector is expressed as

$$\dot{Q}_{loss} = U A_r (T_c - T_a)$$

The useful heat transferred to the fluid is

$$\dot{Q}_{useful} = \dot{Q}_r - \dot{Q}_{loss} = \eta_{ar} A_a G - U A_r (T_c - T_a)$$

The efficiency of this solar collector is defined as

$$\eta_c = \frac{\dot{Q}_{useful}}{\dot{Q}_{incident}} = \frac{\eta_{ar} A_a G - U A_r (T_c - T_a)}{A_a G} = \eta_{ar} - \frac{U (T_c - T_a)}{CR \times G}$$

CONCENTRATING SOLAR COLLECTOR

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The efficiency of a solar system used to produce electricity may be defined as the power produced divided by the total solar irradiation. That is,

$$\eta_{th,solar} = \frac{\dot{W}_{out}}{\dot{Q}_{incident}} = \frac{\dot{W}_{out}}{A_c G}$$

EXAMPLE 4-3 Two concentrating collectors (collector A and collector B) have the same concentration factor of CR = 9 and the optical efficiency of har = 0.85. The collector temperature for both collectors is 350°F and the ambient air temperature is 85°F. The heat loss coefficient for collector A is 0.45 Btu/h·ft2 · °F and that for collector B is 0.63 Btu/h·ft2 · °F. The solar irradiation on collector A is 180 Btu/h·ft2. Determine the solar irradiation rate of collector B so that both collectors have the same efficiency.

Solution The collector efficiency of collector A is determined from

$$\eta_{c,A} = \eta_{ar} - U_A \frac{(T_c - T_a)}{CR \times G_A}$$

$$= 0.85 - (0.45\,Btu/h.ft^2.F)\frac{(350 - 85)F}{(9)(180\,Btu/h.ft^2)} = 0.7764$$

Using the same relation for collector B at the same collector efficiency, we obtain the necessary solar irradiation rate:

$$\eta_{c,B} = \eta_{ar} - U_B \frac{(T_c - T_a)}{CR \times G_B}$$

$$0.7764 = 0.85 - (0.63\,Btu/h.ft^2.F)\frac{(350 - 85)F}{9G_B}$$

$$G_B = 252\,Btu/h.ft^2$$

EXAMPLE 4-4 **Oklahoma City or Portland are considered for the installation of a solar power plant utilizing parabolic trough collectors. The total area of the collectors is 6000 m2 and the average efficiency of the plant is estimated to be 15 percent. Using the average daily solar radiation values on a horizontal surface in Table 3-5 in Chap. 3, determine the amount of electricity that can be produced in each city.**

Solution The average daily solar radiation value on a horizontal surface is obtained from Table 3-5 in Chap. 3 for each city as

$$G_{avg,Ok} = \left(17.15\ ^{MJ}/_{m^2.day}\right)(365 days) = 6250\ ^{MJ}/_{m^2}$$

$$G_{avg,Po} = \left(12.61\ ^{MJ}/_{m^2.day}\right)(365 days) = 4603\ ^{MJ}/_{m^2}$$

Noting that the average thermal efficiency is 15 percent and the total collector area is 6000 m2, the amount of electricity that can be produced in each city would be

$$Amount\ of\ electricity\ (Oklahoma\ City) = \eta_{th} A G_{avg,Ok}$$

$$=(0.15)(6000\ m^2)(6250\ ^{MJ}/_{m^2})\left(\frac{1000\ kJ}{1MJ}\right)\left(\frac{1\ kWh}{3600kJ}\right)$$

$$= 1.565 \times 10^6\ kWh$$

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$$\text{Amount of electricity (Portland)} = \eta_{th} A G_{avg,Po}$$
$$= (0.15)(6000\ m^2)(4603\ {}^{MJ}/_{m^2})\left(\frac{1000\ kJ}{1MJ}\right)\left(\frac{1\ kWh}{3600kJ}\right)$$
$$= 1.151 \times 10^6\ kWh$$

That is, 36 percent more electricity can be generated in Oklahoma City than in Portland.

SOLAR-POWER-TOWER PLANT

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A solar-power-tower plant uses a large array of mirrors called heliostats that track the sun and reflects solar radiation into a receiver mounted on top of a tower (Fig. 4-7). Water is heated by absorbing heat from the receiver system. The resulting steam is directed to a turbine to produce power. A generator is connected to turbine to convert turbine shaft power into electricity.

Figure 4-7
A solar-power-tower plant uses large array of mirrors called heliostats that track the sun and reflect solar radiation into a receiver mounted on top of a tower.

SOLAR-POWER-TOWER PLANT

Ivanpah solar power plant started commercial operation in 2013 after a 3-year construction period, and consists of three separate units (Fig. 4-8). The electricity generated can serve 140,000 homes during the peak hours of the day. The plant is located in Mojave desert in California and is the largest solar thermal power plant in the world with a capacity of 377 MW.

Figure 4-8
Ivanpah solar thermal power plant.

SOLAR-POWER-TOWER PLANT

The solar energy is absorbed by water flowing in the pipes of the boiler. The water turns into superheated vapor, which is directed into a steam turbine located at the bottom of the tower (Fig. 4-9). Electrical output from the turbine is sent to transmission lines. This plant uses air-cooled condenser, which uses 95 percent less water than wet-cooled solar thermal plants.

Figure 4-9
One of the three plants of Ivanpah solar system showing main components.

EXAMPLE 4-5 **5 A solar-power-tower plant is considered for Tucson, Arizona. Heliostats with a total area of 80,000 m2 are to be used to reflect solar radiation into a receiver. When the solar irradiation is 950 W/m2, steam is produced at 2 MPa and 400°C at a rate of 20 kg/s. This steam is expanded in a turbine to 20 kPa pressure. The isentropic efficiency of the turbine is 85 percent. (a) Determine the power output and the thermal efficiency of the plant when the solar radiation is 950 W/m2.**

(b) How much electricity can be produced per year if the average thermal efficiency is 15 percent and the generator efficiency is 96 percent?

Solution (a) Using the turbine isentropic efficiency, the steam properties at the inlet and exit of the turbine are determined as follows (Tables A-3, A-4, and A-5):

$$\left.\begin{matrix} P_1 = 2\ MPa \\ T_1 = 400\ C \end{matrix}\right\} h_1 = 3248.4\ {}^{kJ}/_{kg},\ s_1 = 7.1292\ kJ/kgK$$

$$\left.\begin{matrix} P_2 = 20\ kPa \\ s_2 = s_1 \end{matrix}\right\} h_{2s} = 2349.7\ {}^{kJ}/_{kg}$$

$$\eta_T = \frac{h_1 - h_2}{h_1 - h_{2s}} \rightarrow h_2 = h_1 - \eta_T(h_1 - h_{2s})$$

$$= 3248.4 - (0.85)(3248.4 - 2349.7)$$

$$= 2484.5\ kJ/kg$$

Then the power output is

$$\dot{W}_{out} = \dot{m}(h_1 - h_2) = (20\, kg/s)(3248.4 - 2484.5)\, kJ/kg = 15,280\, kW$$

The thermal efficiency of this power plant is equal to power output divided by the total solar incident on the heliostats:

$$\eta_{th} = \frac{\dot{W}_{out}}{AG} = \frac{15,280\, kW}{(80,000\, m^2)(0.95\ kW/m^2)} = 0.201\ or\ 20.1\%$$

(b) The solar data for Tucson, Arizona is given in Table 3-5 in Chap. 3. The daily average solar irradia tion for an entire year on a horizontal surface is given to be 20.44 MJ/m2 ·day. Multiplying this value with 365 days of the year gives an estimate of solar irradiation on the heliostat surfaces. Using the definition of the thermal efficiency,

$$W_{out} = \eta_{th,avg} A G$$

$$= (0.15)(80{,}000\ m^2)(20{,}440\ kJ/m^2.day)(365\ days)\left(\frac{1\ kWh}{3600\ kJ}\right)$$

$$= 2.487 \times 10^7\ kWh$$

This is total work output from the turbine. The electrical energy output from the generator is

$$W_{elect} = \eta_{gen} W_{out} = (0.96)(2.487 \times 10^7\ kWh) = 2.387 \times 10^7\ kWh$$

This solar power plant has a potential to generate 24 millions kWh of electricity per year. If the elec tricity is sold at a price of $0.10/kWh, the potential revenue from selling of electricity is $2.4 millions per year.

SOLAR POND

A promising method of power generation involves collecting and storing solar energy in large artificial lakes a few meters deep, called solar ponds.

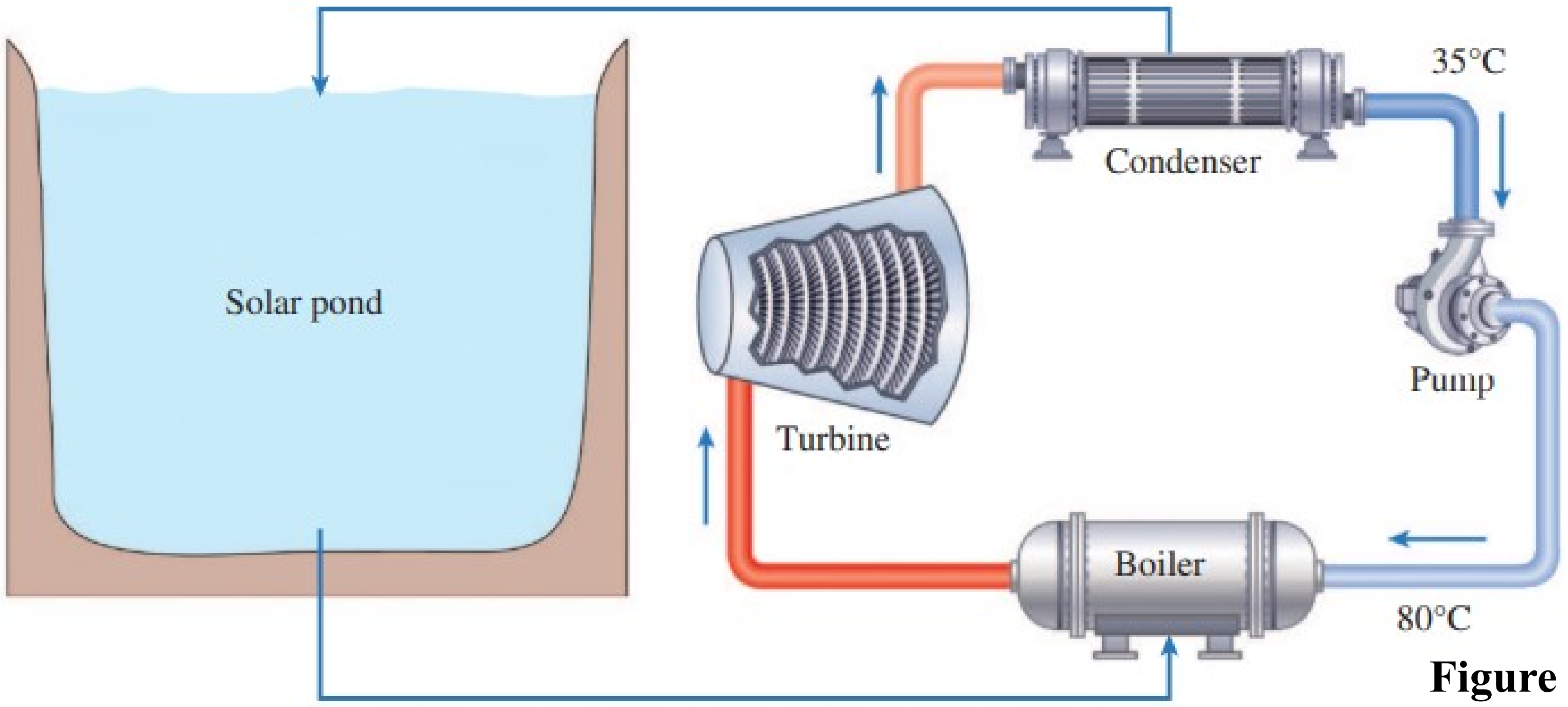

Figure 4-10
Operation of a solar pond power plant.

PHOTOVOLTAIC CELL

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Photovoltaic systems convert electromagnetic radiation into electricity. A photovoltaic system consists of an array of solar cells. The cell involves a p-type semiconductor and an n-type semiconductor. Silicon is commonly used as a semiconductor material in solar cells. The silicon is doped with phosphorus to produce the n-type semiconductor while it is doped with boron to produce the p-type semiconductor. There is a current density flow at the p-n junction of a solar cell (Fig. 4-11).

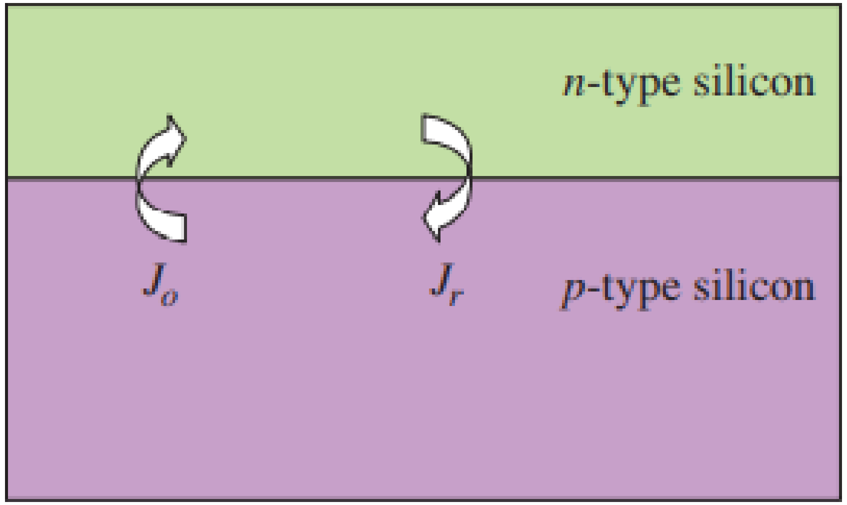

Figure 4-11
A simplified model for current density at p-n junction.

PHOTOVOLTAIC CELL

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The current density J is defined as the current I over the cell surface area A. The current density flow from n-type semiconductor to p-type semiconductor is denoted by Jr and called the light-induced recombination current, and that from p-type to n-type is denoted by Jo and called the dark current or reverse saturation current. In an illuminated solar cell, the Jr is proportional to Jo according to the relation

$$J_r = J_o exp(\frac{e_o V}{kT}) = (0.96)(2.487 \times 10^7\ kWh) = 2.387 \times 10^7\ kWh$$

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where eo = 1.6 × 10−19 J/V is equal to charge of one electron, k = 1.381 × 10−23 J/K is Boltzmann's constant, V is voltage, and T is the cell temperature. The junction current density Jj is equal to algebraic sum of Jr and Jo:

$$J_j = J_r - J_o = J_o[exp\left(\frac{e_oV}{kT}\right) - 1]$$

The load current density JL is given by

$$J_L = J_s - J_j = J_s - J_o[exp\left(\frac{e_oV}{kT}\right) - 1]$$

the open circuit voltage, Voc:

$$V_{oc} = \frac{kT}{e_o} ln(\frac{J_s}{J_o} + 1)$$

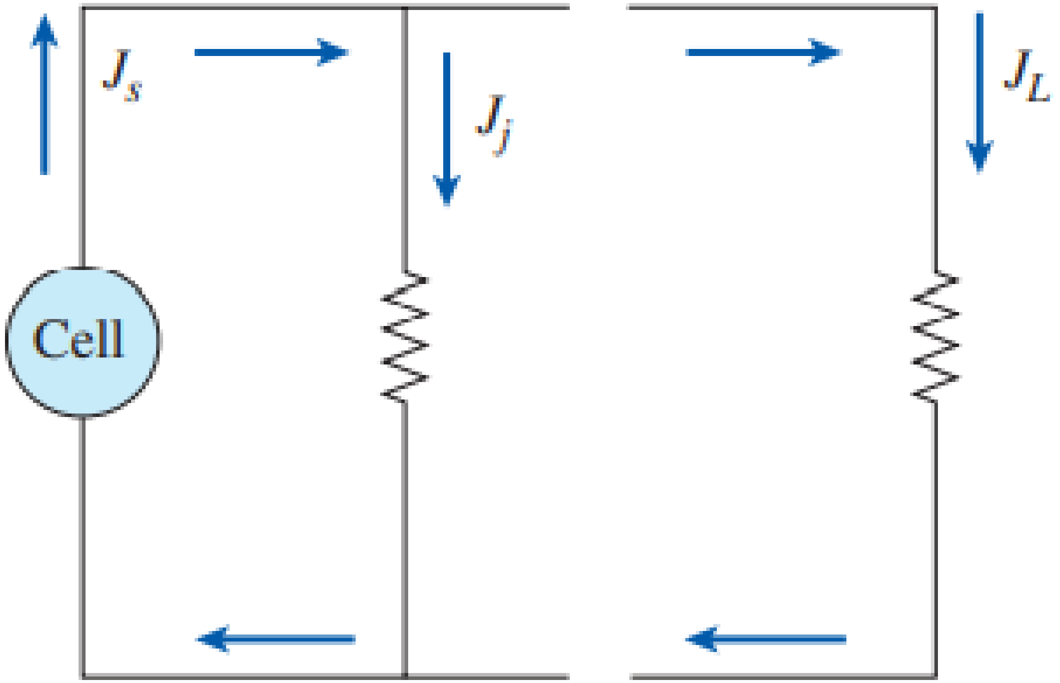

Figure 4-12
Equivalent circuit for solar cell.

PHOTOVOLTAIC CELL

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An expression for the ratio of the load current density JL to short circuit current density JS may be obtained by:

$$\frac{J_L}{J_s} = 1 - \frac{J_o}{J_s}\left[exp\left(\frac{e_oV}{kT}\right) - 1\right]$$

The power output delivered to the load is

$$\dot{W} = J_L VA = VA\,J_s - VAJ_o\left[exp\left(\frac{e_oV}{kT}\right) - 1\right]$$

Differentiating above Eq. with respect to voltage V and setting the derivative equal to zero gives the maximum load voltage for the maximum power output:

$$exp\left(\frac{e_oV_{max}}{kT}\right) = \frac{1 + J_s/J_o}{1 + \frac{e_oV_{max}}{kT}}$$

PHOTOVOLTAIC CELL

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The maximum power output of the cell is

$$\dot{W}_{max} = \frac{AV_{max}(J_s + J_o)}{1 + \frac{kT}{e_o V_{max}}}$$

The conversion efficiency of a solar cell can be expressed as the power output divided by the incident solar radiation:

$$\eta_{cell} = \frac{\dot{W}}{AG}$$

The maximum conversion efficiency of a solar cell can be written as

$$\eta_{cell,max} = \frac{\dot{W}_{max}}{AG} = \frac{AV_{max}(J_s + J_o)}{AG(1 + \frac{kT}{e_o V_{max}})} = \frac{V_{max}(J_s + J_o)}{G(1 + \frac{kT}{e_o V_{max}})}$$

PHOTOVOLTAIC CELL

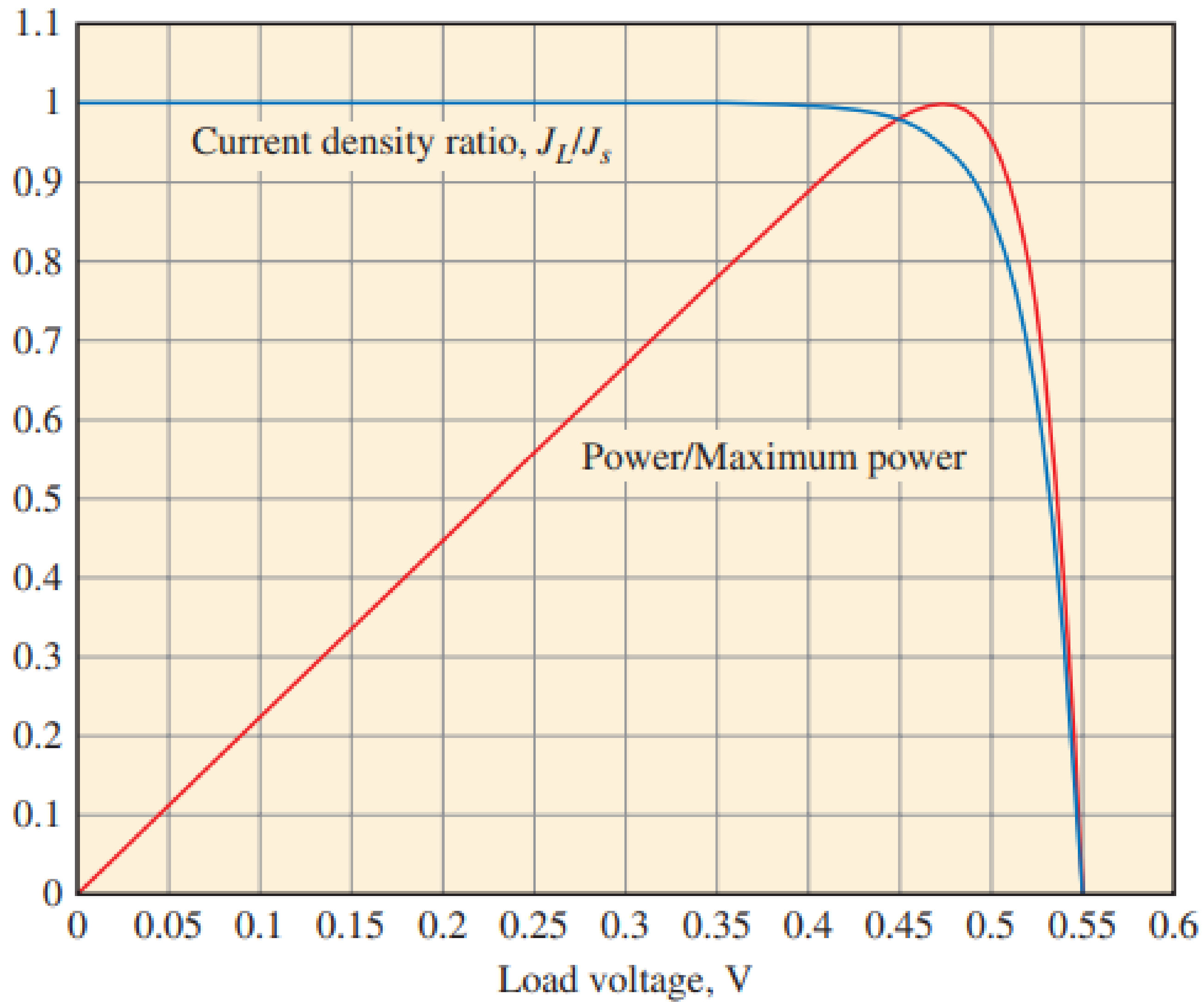

Figure 4-13
Current density ratio JL/Js and power output ratio $\dot{W}/\dot{W}_{max}$ in a solar cell as a function of load voltage.

EXAMPLE 4-6 A solar cell has an open circuit voltage value of 0.62 V with a reverse saturation current density of 2.253×10^{-9} A/m2.

(a) For a temperature of 20°C, determine the load voltage at which the power output is maximum.

(b) If the solar irradiation is 770 W/m2, determine the efficiency of the solar cell at a load voltage of 0.5 V.

(c) Determine the cell area for a power output of 500 W at a load voltage of 0.5 V.

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Solution (a) The current output density is determined from

$$V_{oc} = \frac{kT}{e_o} ln(\frac{J_s}{J_o} + 1)$$

$$0.62\, V = \frac{(1.381 \times 10^{-23}\, J/K)(293K)}{1.6 \times 10^{-19}\, J/V} ln(\frac{J_s}{2.253 \times 10^{-9}\, A/m^2} + 1)$$

$$J_s = 100A/m^2$$

The load voltage at which the power output is maximum is determined from

$$exp\left(\frac{e_o V_{max}}{kT}\right) = \frac{1 + J_s/J_o}{1 + \frac{e_o V_{max}}{kT}}$$

$$exp\left(\frac{e_oV_{max}}{kT}\right)=\frac{1+J_s/J_o}{1+\frac{e_oV_{max}}{kT}}$$

$$exp\left(\frac{(1.6\times10^{-19}\,J/V)V_{max}}{(1.381\times10^{-23}\,J/K)(293\,K)}\right)=\frac{(1+100^{A}/_{m^2}/2.253\times10^{-9\,A}/_{m^2})}{1+\frac{(1.6\times10^{-19}\,J/V)V_{max}}{(1.381\times〖10〗^(-23)\ J/K)(293\,K)}}$$

$$V_{max}=0.5414\,V$$

(b) The load current density is determined from:

$$\frac{J_L}{J_s}=1-\frac{J_o}{J_s}\left[exp\left(\frac{e_oV}{kT}\right)-1\right]$$

$$\frac{J_L}{100\,A/m^2}=1-\frac{2.253\times10^{-9\,A}/_{m^2}}{100^{A}/_{m^2}}\left[exp\left(\frac{(1.6\times10^{-19}\,J/V)(0.5\,V)}{(1.381\times10^{-23}\,J/K)(293\,K)}\right)-1\right]$$

$$J_L=99.12A/m^2$$

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The power output per unit area of the cell is

$$\dot{W}/A = J_L V = 99.12 A/m^2)(0.5\ \mathrm{V})\left(\frac{1W}{1AV}\right) = 49.56\ \mathrm{W}/m^2$$

Then, the cell efficiency becomes

$$\eta_{cell} = \frac{\dot{W}/A}{G} = \frac{49.56\ \mathrm{W}/m^2}{770\ \mathrm{W}/m^2} = 0.0644\ or\ 6.44\%$$

(c) Finally, the cell area the cell area for a power output of 500 W is

$$A = \frac{\dot{W}}{\dot{W}/A} = \frac{500\ W}{49.56\ \mathrm{W}/m^2} = 10.1\ m^2$$

Solar radiation incident on a solar cell is originated from the sun. The upper limit for the efficiency of a solar cell may be determined from the Carnot efficiency by using effective surface temperature of the sun (5780 K) and an ambient temperature of 298 K:

$$A = \frac{\dot{W}}{\dot{W}/A} = \frac{500\ W}{49.56\ W/m^2} = 10.1\ m^2$$

(c) Finally, the cell area the cell area for a power output of 500 W is

$$\eta_{cell,max} = 1 - \frac{T_L}{T_H} = 1 - \frac{298\ K}{5780\ K} = 0.948\ or\ 94.8\%$$

PHOTOVOLTAIC CELL

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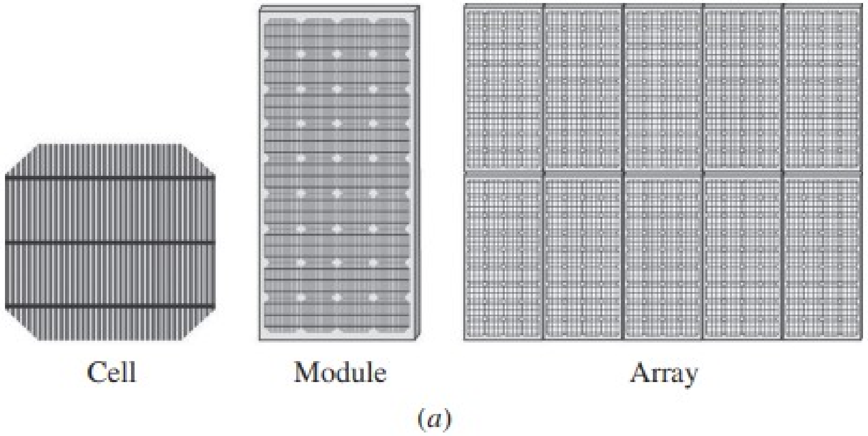
A single solar cell produces only 1 to 2 W of power. Multiple cells should be connected to form modules and modules should be connected into arrays so that reasonable amounts of power can be generated (Fig. 4-14). This way, both small and large photovoltaic systems can be installed depending on the demand.

The lifespan of a solar cell is about 20 to 35 years.



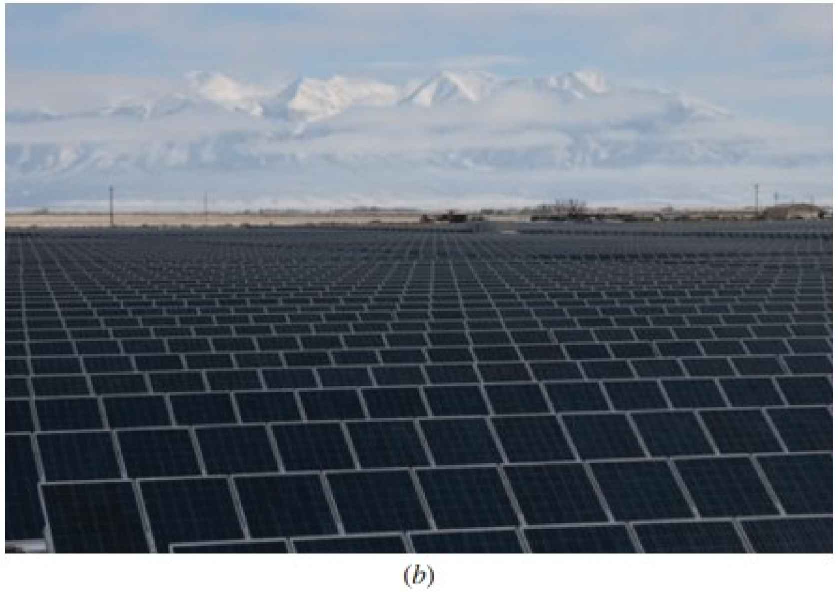


Figure 4-14
(a) A photovoltaic system typically consists of arrays, which are obtained by connecting modules, and modules consist of individual cells.
(b) Solar arrays.

PASSIVE SOLAR APPLICATIONS

The use of solar energy by means of engineering design without the involvement of mechanical equipment is called passive use of solar energy.

In this section, we describe a trombe wall and analyze solar heat gain through windows as common examples of passive solar applications.

Trombe Wall

Dark-painted thick masonry walls called trombe walls are commonly used on south sides of passive solar homes to absorb solar energy, store it during the day, and release it to the house during the night.

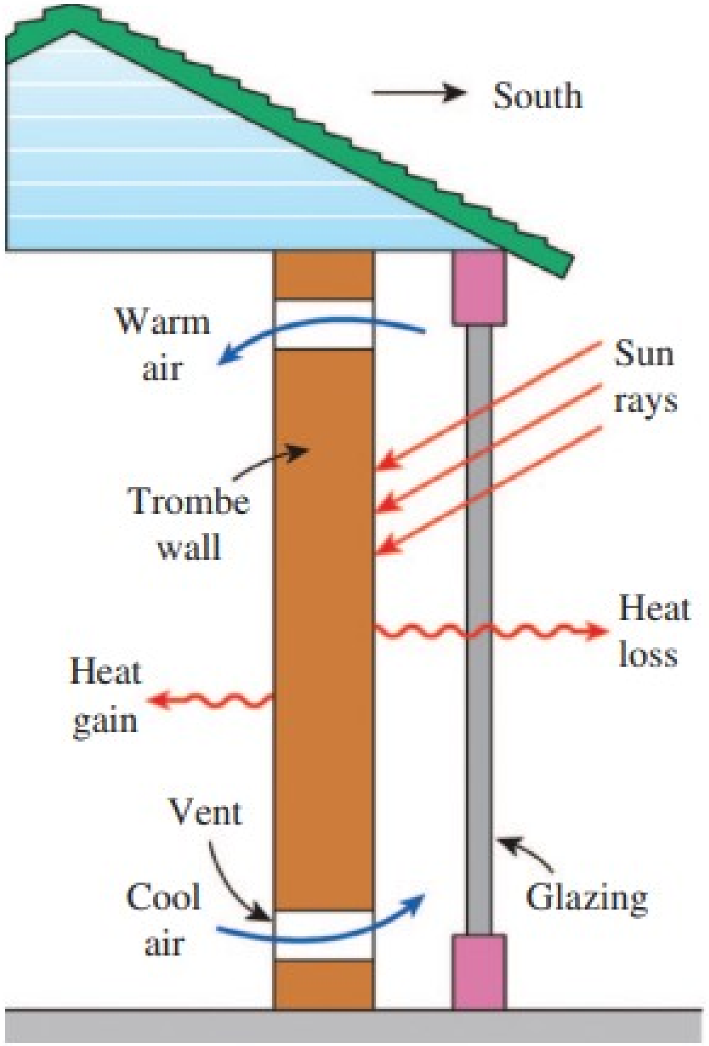


Figure 4-15
Schematic of a trombe wall.

Solar Heat Gain through Windows

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The radiation reaching a surface, in general, consists of three components: direct radiation, diffuse radiation, and radiation reflected onto the surface from surrounding surfaces

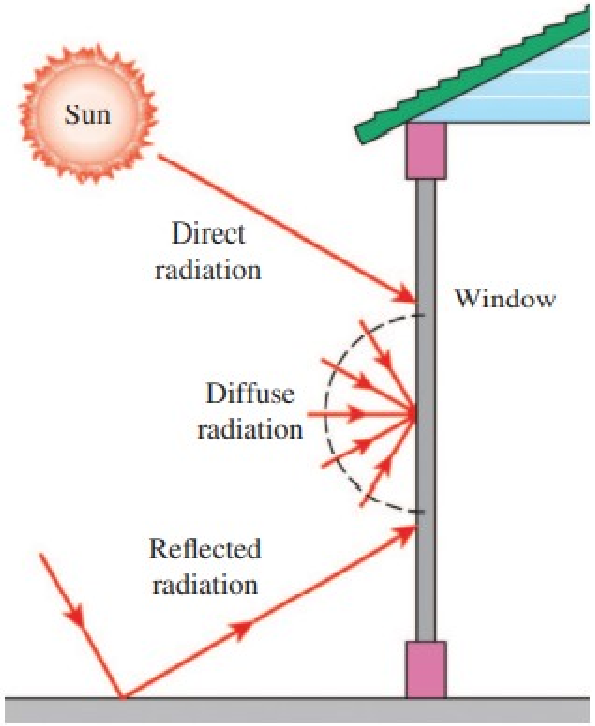

Figure 4-16
Direct, diffuse, and reflected components of solar radiation incident on a window

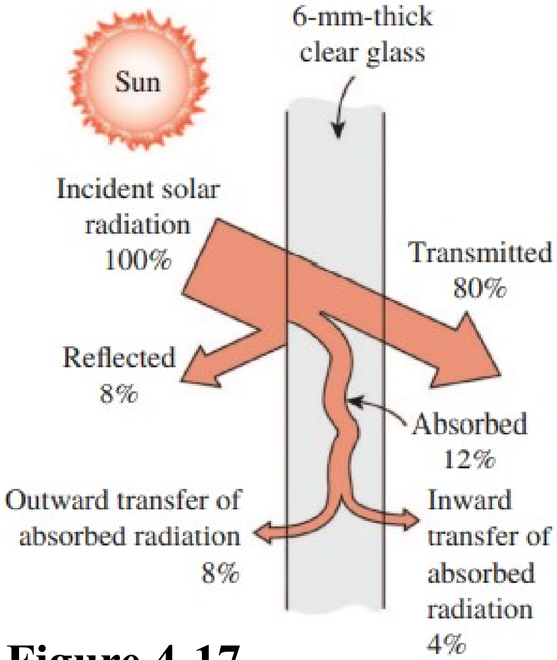

Figure 4-17
Distribution of solar radiation incident on a clear glass.

Solar Heat Gain through Windows

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The fraction of incident solar radiation that enters through the glazing is called the solar heat gain coefficient (SHGC) and is expressed as

$$SHGC = \frac{\dot{q}_{solar,gain}}{G} = \tau_s + f_i \alpha_s$$

The total solar heat gain through that window is determined from

$$\dot{Q}_{solar,gain} = SHGC \times A_{glazing} \times G$$

Solar Heat Gain through Windows

Another way of characterizing the solar transmission characteristics of different kinds of glazing and shading devices is to compare them to a well-known glazing material that can serve as a base case. This is done by taking the standard 3-mm-thick (⅛-in) double strength clear window glass sheet whose SHGC is 0.87 as the reference glazing and defining a shading coefficient (SC) as

$$SC = \frac{SHGC}{SHGC_{ref}} = \frac{SHGC}{0.87} = 1.15 \times SHGC$$

EXAMPLE 4-7 Two window options are considered for a new house with a floor area of 250 m2. Windows occupy 16 percent of floor area and equally distributed in all four sides. Windows options are

Option 1: Double-glazed window, clear glass, air fill, U-factor = 4.18 W/m2 ·K, SHGC = 0.77

Option 2: Double-glazed window, low-e glass, argon gas fill, U-factor = 1.42 W/m2 ·K, SHGC = 0.39

The average daily solar heat fluxes incident on all four sides is given in kWh/m2 ·day during summer cooling months as follows:

June: 4.95 July: 4.80 August: 4.55 September: 3.95

(a) Determine the total amount of heat gain through the windows in summer. Take the average outside and indoor temperatures in summer to be 35 and 23°C, respectively.

(b) If the coefficient of performance (COP) of the cooling system is 2.3, determine the net cooling cost savings in summer due to using window option 2. Take the unit cost of electricity to be \$0.11/kWh.

Solution (a) The total window area is 16 percent of the floor area:

$$A_{window} = (0.16)(0.250\ m^2) = 40\ m^2$$

The number of hours in summer months is

$$Summer\ hours = (30 + 31 + 31 + 30) \times 24\ h = 2928\ h$$

The total solar heat flux incident on the glazing during summer months is determined to be

$$q_{solar} = (4.95\ kWh/m^2\ .\text{day} \times 30\ days) + (4.80\ kWh/m^2.\text{day} \times 31\ days) + (4.55\ kWh/m^2.\text{day} \times 31\ days) + (3.95\ kWh/m^2.\text{day} \times 30\ days) = 556.9\ kWh/m^2$$

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Calculations for window option 1:

The rate of heat transfer through the windows in winter is

$$\dot{Q}_{transfer} = U_{overall} A_{window} (T_o - T_i)$$
$$= (4.18\ W/m^2.C)(40m^2)(35 - 23)C = 2006\ W$$

The amount of heat transfer through the windows is

$$Q_{transfer} = \dot{Q}_{transfer} \times Summer\ hours = (2.006\ kW)(2928\ h)$$
$$= 5875\ kWh$$

The amount of solar heat input is

$$Q_{solar} = SHGC \times A_{window} \times q_{solar} =$$
$$(0.77)(40\ m^2)(556.9\ kWh/m^2) = 17,153\ kWh$$

The total amount of heat input through windows is

$$Q_{total} = Q_{transfer} + Q_{solar} = 5875 + 17,153 = 23,028\ kWh$$

Calculations for window option 2:

The rate and amount of heat transfers through the windows are

$$\dot{Q}_{transfer} = U_{overall} A_{window} (T_o - T_i)$$
$$= (1.42\ W/m^2.C)(40m^2)(35 - 23)C = 682\ W$$

$$Q_{transfer} = \dot{Q}_{transfer} \times Summer\ hours = (0.682\ kW)(2928\ h)$$
$$= 1996\ kWh$$

The amount of solar heat input in summer for this window is

$$Q_{solar} = SHGC \times A_{window} \times q_{solar} =$$
$$(0.39)(40\ m^2)(556.9\ kWh/m^2) = 8688\ kWh$$

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The total amount of heat input is

$$Q_{total} = Q_{transfer} + Q_{solar} = 1996 + 8688 = 10,684\ kWh \approx 10,700\ kWh$$

(b) The decrease in heat input in summer due to using window option 2 is

$$23,028 - 10,684 = 12,344\ kWh$$

This corresponds to a reduction of 53.6 percent.

The corresponding decrease in cooling cost is determined from

$$\textit{cooling cost savings} = \frac{\textit{cooling load decrease} \times \textit{unit cost of electricity}}{COP}$$

$$= \frac{12,344\ kWh)(\$0.11/kWh)}{2.3} = \$590$$

The window with lower U-factor and SHGC saves the house $590 in summer cooling costs. It should be noted that the amount of heat loss through windows will also be lower in winter due to lower U-factor of window option 2. However, there will be less solar heat gain in winter due to lower SHGC.