# Chapter 7
# Solar Energy

**Abstract** At an average rotational radius around the Sun of $1.49*10^{11}$ m and with an average radius of 6,378 km, the planet Earth receives solar radiation power of approximately $1.73*10^{14}$ kW, a quantity that surpasses by far all the power requirements of the Earth's inhabitants. This continuously received power, which is called *incident solar radiation* and shortened to *insolation*, integrates to a total energy of $5.46*10^{21}$ MJ per year, or more than 100 million times the total energy used by earthlings in a year. This tremendous amount of energy is abundant, free of charge, almost uniformly distributed and available to all nations and inhabitants of the planet. However, only a very small fraction of the incident solar radiation is used by the Earth's population. Passive solar heating systems provide with space heating and hot water a low fraction of the buildings, primarily in OECD countries, while thermal solar power plants and photovoltaic cells provide a small fraction of the electricity consumed. Despite its low utilization at present, and because of the enormous amounts of power reaching the Earth, solar energy is a prime alternative energy source and has the potential to supply a very high fraction, if not all, of the power used by the Earth's population. This chapter starts with a short exposition on the amount of solar energy available and continues with the exposition of the two main families of systems that are currently used for power production from solar energy: solar thermal systems and photovoltaic systems. Photovoltaic solar cells and solar thermal systems utilize the solar energy in entirely different ways and are examined separately. Emphasis is given on the electric power production by solar energy as well as the current and proposed systems used for electric power production. A brief mention of the passive heating systems and the environmental effects of solar energy utilization are also included in the chapter.

E. E. (Stathis) Michaelides, *Alternative Energy Sources*,
Green Energy and Technology, DOI: 10.1007/978-3-642-20951-2_7,

## 7.1 Earth-Sun Mechanics and Solar Radiation

With a period of one year, which is approximately defined as 365.25 days, the Earth rotates around the Sun in a slightly elliptical orbit. This orbit has major and minor axes equal to $1.54*10^{11}$ and $1.45*10^{11}$ m. The Earth also rotates daily around its polar axis, which is directed from the North Pole to the South Pole. The polar axis is at a constant inclination of $23.45^{\circ}$ to the plane of the elliptical orbit. The Earth's inclination causes the differential energy absorption by the two hemispheres of the Earth and causes the seasonal variations of solar radiation, the local temperature variations, the local wind patterns and the local seasonal weather. Figure 7.1a shows the position of the Earth on four days of the year, which characterize the beginning of the four seasons in the northern hemisphere: winter, spring, summer, and autumn (fall) respectively: a) the winter solstice (it usually occurs on December 21); b) the vernal (spring) equinox[1] (usually on March 20); the summer solstice (usually on June 21) and the autumnal equinox (usually on September 23). Figure 7.1b shows the polar axis (PA) and the axis of the elliptical orbit (OA) during these 4 days of the year. The slightly different duration of the four seasons is due to the elliptical orbit of the Earth, which makes the position of the Earth to be closer to the Sun during the winter season for the northern hemisphere. According to Keppler's laws the translational speed of the Earth is also highest during the winter. As a consequence, the winter season in the northern hemisphere is slightly shorter and the summer season is longer than the other seasons. The opposite holds for the southern hemisphere.

It is apparent from Fig. 7.1a that, with the exception of the two equinox days, the two hemispheres of the Earth receive different amounts of solar radiation. This causes the development of the seasons and the seasonal variations of climate and weather. Given the combination of the two motions, the rotation of the Earth around its polar axis and the motion of the Earth around the Sun, the intensity of the solar energy received by any point on Earth varies significantly, but varies in a predictable way. A stationary receiver of solar energy would receive power in a periodic manner, based on two timescales: diurnal and annual. This receiver will only receive energy during the daytime hours. If the receiver is in the northern hemisphere, it will receive more energy during a summer day than during a winter day, simply because the summer daytime is longer. This type of reasoning has led many to characterize solar energy as *intermittent.* A moment's reflection, however, would prove that the variability of insolation at a given terrestrial location is periodic and is based on the distance of the Earth from the Sun and its orientation.

[1] *Solstice* may be roughly translated as the day when the sun stands still in the sky and *equinox* (equal night) implies that daytime and nighttime are equal. During the two solstices the sun is at the northernmost and the southernmost points. At these points the sun appears to stop moving and reverses its direction, thus receding towards the equator. Despite the meaning of the term, during the two equinoxes, day and night are not exactly equal because of the refraction and diffusion of the sunlight, which is caused by the atmosphere of the Earth.

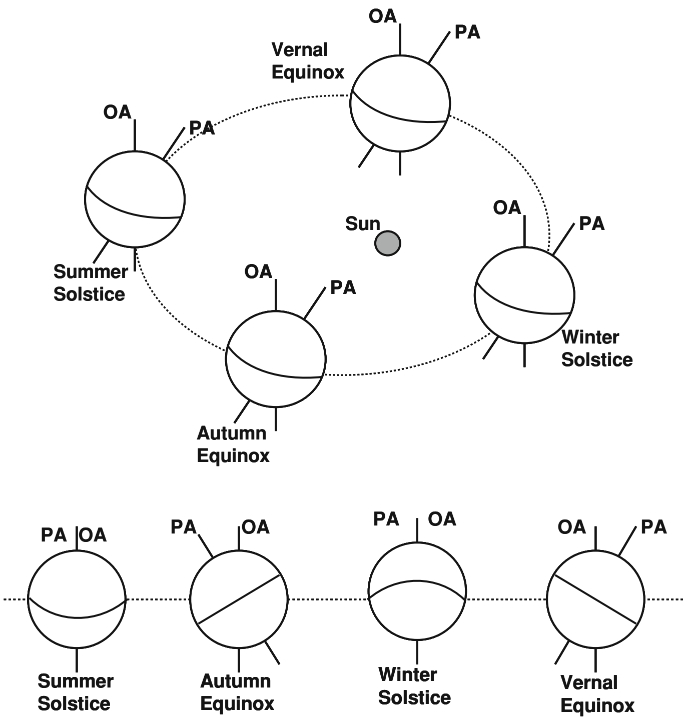



**Fig. 7.1** **a** The elliptical orbit of Earth around the Sun and **b** The Earth's orientation relative to its orbit around the Sun. PA is the polar axis and OA is the axis of the plane of the elliptic orbit

The latter are periodic functions of the annual and diurnal rotations of the Earth. Cloudiness, humidity, pollution and other temporal variables that affect the insolation at a specific location provide a small amount of almost random perturbation to the local insolation. As a consequence, we know with a high degree of certainty that during the week of July 10–17, solar collectors in Arizona will collect a great deal of incident radiation, while during the week of December 7–14 the solar energy that will be collected by the same collectors is significantly lower. Therefore, a better way to characterize insolation and solar energy is *predictably variable* or *periodic.*

The power emitted by the Sun is homogeneous in all directions. A fundamental quantity that characterizes the incident solar radiation or insolation is the *solar constant*, which is the power received by a unit area, perpendicular to the solar rays and is located outside the Earth's atmosphere. The solar constant, *S*, which is approximately equal to 1.353 kW/m$^2$ or 4.871 MJ/(hr*m$^2$) or 438 Btu/(hr*ft$^2$) or 1.940 Langley/min, is the yearly average power a collector would receive outside the Earth's atmosphere, when it is faced perpendicularly to the Sun's rays. S is not exactly a constant, because the distance of the Earth from the Sun is variable, with a period of one year. However, the amplitude of the variation of the Earth's radius, or distance from the Sun, is small enough (3%) for the insolation to be considered almost constant.

### *7.1.1 Solar Spectrum and Insolation on a Terrestrial Surface*

It is well known that the Sun's radiation is not monochromatic. The Sun's radiation has the characteristics of a black-body radiation at approximately 5,762 K. The full spectrum of power that is emitted by the Sun may be intercepted at the outer atmosphere. When the Sun's radiation enters the terrestrial atmosphere, the various elements that constitute the atmosphere absorb preferentially parts of this spectrum. Among these, oxygen, water vapor and carbon dioxide absorb a great deal of the solar radiation at discrete wavelengths in the visible light and the infrared part of the solar spectrum. Therefore, when the solar radiation is received at the surface of the Earth, part of the energy of the radiation has already been absorbed and several parts of the solar spectrum are missing because of this preferential absorption.

The amount of energy absorbed depends on the thickness of the atmosphere the solar rays have to pass in order to reach the surface of the Earth. For example, during the equinox, where the Sun is directly above the equator, the Sun's radiation has to pass through the minimum amount of air mass to reach the surface of the equator. This is usually denoted as m = 1, with the parameter m indicating the "mass" of air the Sun rays must travel to reach a specific location. During the winter days, when the Sun is in the southern hemisphere, the Sun rays have to travel through a thicker air path to reach locations in the northern hemisphere, such as New York or Germany. During winters the parameter m for New York City is close to 3 and for some locations in Germany it may become as high as 4.2, which indicates that a great deal of the insolation has been absorbed by the atmospheric constituents. According to this notation, the solar radiation outside the atmosphere and the solar constant $S = 1.353\ \text{kW/m}^2$ would correspond to $m = 0$. Clearly, the parameter $m$ is closely related to the geographic latitude of the location.

The Sun may be accurately approximated as a *black-body*, which has several convenient radiation properties. Among these are: a) the power emitted or absorbed is homogeneous and constant in all directions and b) the energy density is a function of the temperature of the black body and given by the expression:

$$I_\lambda = \frac{2\pi hc^2}{\lambda^5\left(\exp\left({}^{hc}/_{\lambda kT}\right) - 1\right)}, \tag{7.1}$$

where $\lambda$ is the radiation wavelength, T is the absolute temperature, $c$ the speed of light ($3*10^8$ m/s), $k$ is the Boltzmann constant ($1.380*10^{-23}$ J/K), and $h$ is Plank's constant ($6.62*10^{-34}$ Js). Since the speed of light is equal to the product of the frequency of radiation $v$ and the wavelength ($c = \lambda v$) the energy density may also be written in terms of the frequency of radiation, $Iv$ as follows:

$$I_v = \frac{2\pi h v^5}{c^3\left(\exp\left(^{hv}/_{kT}\right) - 1\right)}. \tag{7.2}$$

It is apparent from the last two equations that the energy density of the solar spectrum is approximately zero at the two extremities of the spectrum—where $v$ and $\lambda$ are zero and very large respectively—and that the function exhibits a maximum. The maximum of the energy density may be obtained by differentiating either Eq. (7.1) or Eq. (7.2) with respect to $\lambda$ or $v$. Thus, the wavelength $\lambda_{max}$ where the maximum energy density of the spectrum occurs is given by the expression:

$$\lambda_{max} T = 0.0029\, mK. \tag{7.3}$$

This expression is known as *Wien's Law*. The total radiation power, $\dot{W}_{rad}$, emitted by a black body is calculated by integrating the appropriate expression for the energy density, Eq. (7.1) or (7.2) over all the wavelengths or the frequencies and around a sphere that surrounds the black body. The final expression of this integration is:

$$\dot{W}_{rad} = A\int_0^\infty I_\lambda d\lambda = A\int_0^\infty I_v dv = A\sigma T^4. \tag{7.4}$$

where $\sigma$ is the Stephan-Boltzmann constant: $5.67*10^{-8}$ W/($m^2K^4$) and A is the area of the receiver. If the radiating body may not be considered a "black body" then it is a *gray body* and the power emitted by it is multiplied by an empirical correction factor, the emissivity, $\varepsilon$. Equation (3.6) for radiation heat transfer which uses the concept of emissivity and the geometric factor of interaction of two radiating objects has been derived from Eq. (7.4).

Figure 7.2 shows this transformation of the solar spectrum as it passes through the terrestrial atmosphere by depicting the energy density, $I$, of radiation for each wavelength in W/($m^2$ nm). The figure shows three graphs:

a) The solar spectrum outside the atmosphere;
b) The approximate solar spectrum received at the surface of the Earth for $m = 1$ after all the atmospheric effects on the incident radiation; and,
c) The radiation spectrum of a black body at 5,762 K for comparison.

The total insolation in a given location on the Earth's surface may be determined by integrating the local solar spectrum along all the wavelengths or frequencies. This may be accomplished, simply, by a summation process. Following Eq. (7.4) the insolation or total power per unit area, $\dot{W}/$A, received is equal to the integral under the energy intensity curve, that is:

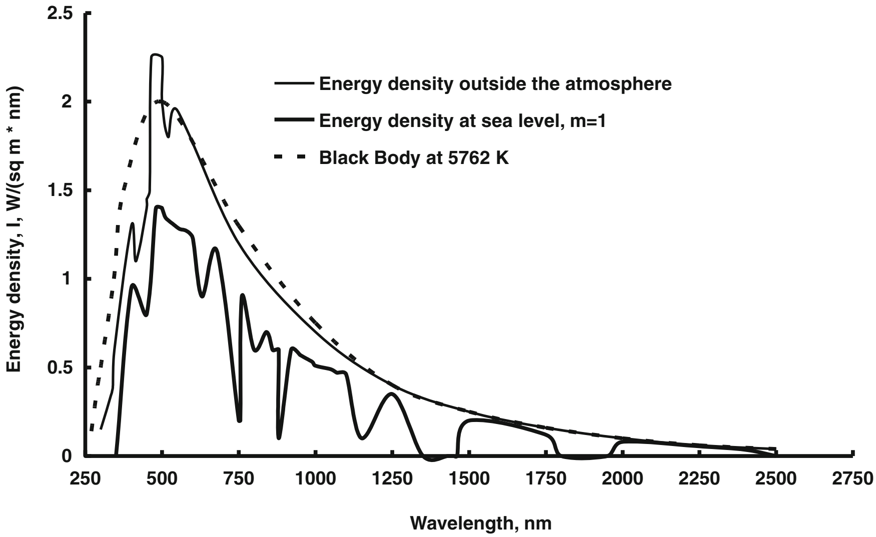



**Fig. 7.2** The solar spectrum in the outer atmosphere and on the terrestrial surface for $m = 1$. The black-body radiation for $T = 5{,}762$ K is given for comparison

$$\frac{\dot{W}_{\mathrm{rad}}}{A} = \int_{0}^{\infty} I_{\lambda} d\lambda. \tag{7.5}$$

It is apparent that $\dot{W}_{\mathrm{rad}}/\mathrm{A}$ is a variable with spatial and temporal dependence.

It is observed in Fig. 7.2 that the solar radiation, which reaches the outer atmosphere, is very close to and may be well approximated by a black body at approximately 5,800 K. It is also seen that the spectrum at the surface of the Earth is significantly different and that the total power that reaches the surface of the Earth—the integral under the graph for $m = 1$—is significantly lower than the total power received by the outer atmosphere. Because of this, the power that reaches the surface of the Earth is significantly lower than the solar constant $S$. On a clear day, the power that reaches the Earth varies from approximately 1 kW/m$^2$ at noon on the equator to <0.2 kW/m$^2$ in Canada and the UK.

Another factor that affects the local insolation is the cloudiness or clarity of the atmosphere. Clouds reflect a great deal of the radiation they receive, while both clouds and fog disperse some of this radiation. Hence, locations with high average cloudiness during the year receive lower average power from the Sun. The diffusion of the solar radiation from clouds, dust and fog in the atmosphere as well as the radiation, which is absorbed by the atmospheric gases, is emitted back in all directions homogeneously. This secondary emission is known as the *diffuse radiation* and contributes to the total radiation received by a terrestrial collector. While absorption and diffusion reduce the power that reaches a location, the secondary emission of the diffuse radiation contributes, sometimes

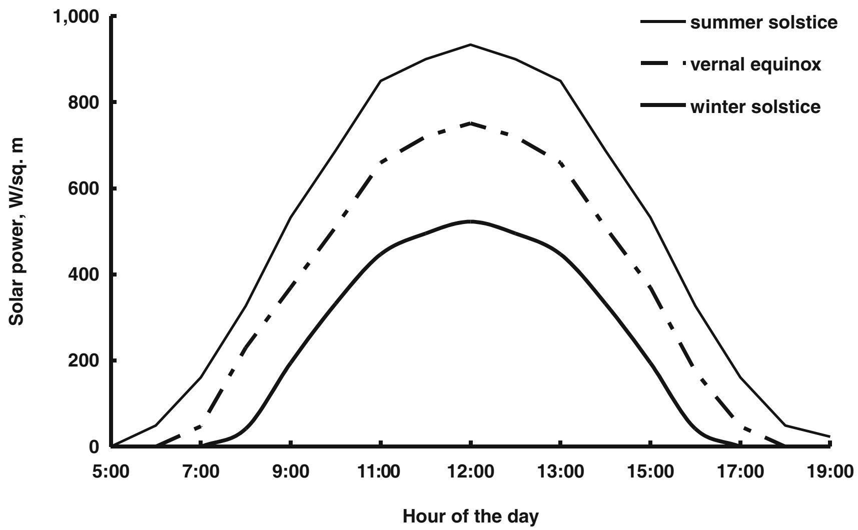



**Fig. 7.3** Solar insolation, in W/m$^2$, received in San Antonio, Texas by a horizontal surface

significantly, to the total power received in several locations, especially on foggy days. For example, in Oxford England, a location known for its high cloudiness, on a bright summer day the direct radiation contributes 7.0 kWh/m$^2$ and the diffused radiation approximately 1.4 kWh/m$^2$ for a total of 8.4 kWh/m$^2$ (the instantaneous insolation was integrated for the entire day in this example). On a dull winter day in the same city the corresponding amounts of direct and diffuse radiation are 0.5 and 0.3 kWh/m$^2$ for a total of 0.8 kWh/m$^2$ during the entire day. Typically, the diffuse radiation amounts from 10 to 40% of the direct radiation on a given location, but, as this example shows, this fraction may exceed 60%.

A third factor that affects the radiation received on a terrestrial location is the time of the day. There is significantly less power during the morning and the afternoon and there is zero solar power during the night. The *solar noon* for a location is the time of the day when the Sun is at its highest point on the horizon and the solar power that reaches the location is at a maximum. Figure 7.3 depicts the solar power per unit area, in W/m$^2$, received in San Antonio, Texas, on 3 days of the year, the two solstices and an equinox. It is evident that the power per unit area received on all days of the year will fall between the curves that correspond to the two solstices. The total energy received during a day is equal to the area under the daily curves:

$$E = \int_{-12}^{12} \dot{W}_{\mathrm{rad}} dt, \tag{7.6}$$

where $t = 0$ represents the solar noon and the time units are hours.

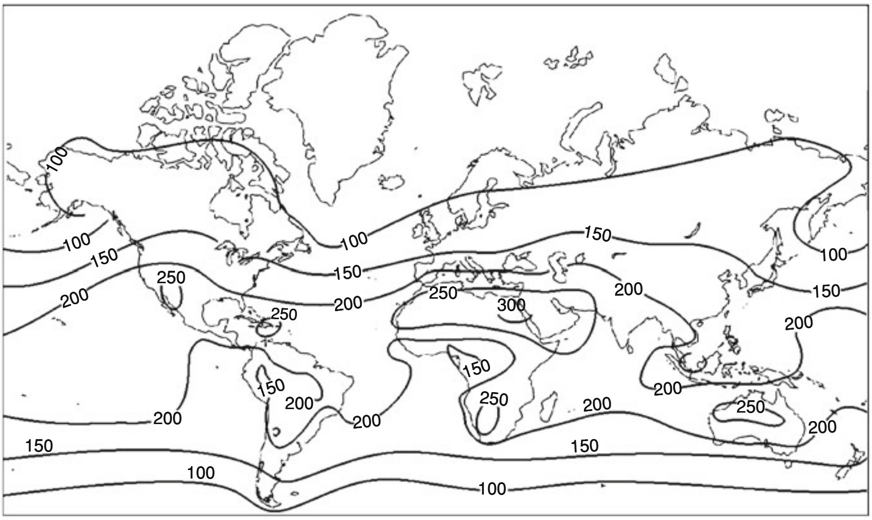



**Fig. 7.4** Contours for the annual average solar radiation on a horizontal surface in $W/m^2$

## *7.1.2 Average Annual Solar Power: Solar Energy Potential*

It is apparent that the total amount of solar energy received by a collector on the surface of the Earth during a day or during a year depends on several factors, most important of which are:

1. The geographic latitude of the location of the collector.
2. The average cloudiness or coverage of the location.
3. The day of the year.
4. The angle of the collector with the horizontal.

Several average quantities are being used to determine the potential of a location to convert solar power to useful energy. Among these are:

1. The maximum daily average power on a horizontal surface ($W/m^2$).
2. The maximum daily energy received by a horizontal surface ($J/m^2$).
3. The annual average incident power on a horizontal surface ($W/m^2$).
4. The annual energy received by a horizontal surface ($W/m^2$).

A solar installation that would convert the incident solar power to thermal or electrical energy operates throughout the year and, therefore, its merits must be evaluated based on the total energy it produces for an entire year, not just a few bright days. For this reason, the yearly averages of energy and power are the best indicators of the solar energy potential in a given location. A global map of the annually averaged incident solar power on a horizontal surface is shown in Fig. 7.4, where the contours depict the average solar power levels.

The contours on this map represent the solar power potential of the Earth's locations, averaged annually, and take into account all the factors that affect the incident solar radiation. A few conclusions may be drawn from this map:

1. Despite the fact that the solar constant is equal to $S = 1.353$ kW/m$^2$ and the maximum incident radiation at an equatorial location is close to 1.0 kW/m$^2$, when the solar radiation is averaged over the entire day and night and over the whole year, the best locations on Earth receive an average of only 250–300 W/m$^2$. These locations are in the Sahara and the Arabian Peninsula, which are considered prime regions for the utilization of solar energy.
2. While the best locations for solar energy conversion are in the equatorial zone, there are several temperate locations where the average annual solar power is close to that observed in the equatorial zones. Most notable among these locations are Mexico and the Southwest of the United States, all the Mediterranean countries, South Africa, Australia, Argentina and Chile. Lower cloudiness and less rainfall in these regions are the reasons for an annually averaged power close to 200 kW/m$^2$.
3. Almost all the OECD countries, where the capital to develop and build solar energy systems is readily available and most of the solar facilities exist today, are located in areas with annually averaged power between 100–200 kW/m$^2$.
4. The geographical area from Pakistan in the East to Korea and Indonesia to the west, where 60% of the Earth's inhabitants live and which is experiencing a high economic growth and very high energy demand growth is within the contours of 150–200 kW/m$^2$. This region has an excellent potential for solar energy utilization. Higher solar energy utilization in these developing economies is not only feasible and advisable but will ease significantly the energy shortage in the world as well as the environmental effects of fossil fuel combustion.

The engineering systems that have been developed for the harnessing of solar energy are divided into two categories:

A. Solar-Thermal systems, which include systems for the storage of heat as well as the production of electricity.
B. Direct Solar-Electric or Photovoltaic systems.

## 7.2 Solar-Thermal Systems

The common characteristic of all Solar-Thermal systems for energy conversion is that they capture the solar radiation as heat and subsequently use this heat primarily for two purposes:

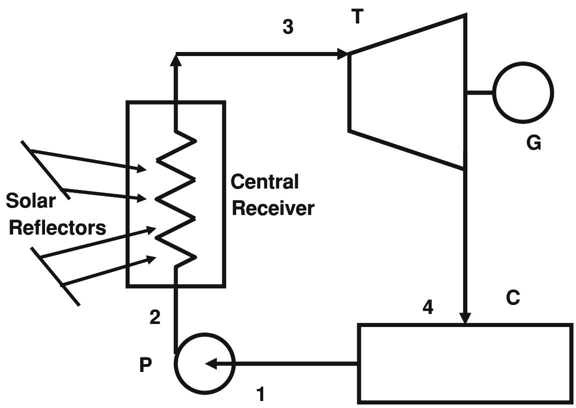



**Fig. 7.5** Essential components of a solar thermal power plant

a) The production of electricity via a conventional thermal cycle, and
b) Residential space or water heating and the supply of heat for commercial and industrial processes.

Solar thermal collectors are required for all these processes. Solar thermal collectors intercept and absorb the Sun's rays and transfer this heat to the pertinent energy conversion system.

### *7.2.1 Power Cycles*

A Rankine cycle (simple or with superheat) is typically used for the electricity production from solar energy. The boiler in this cycle is replaced by a system of solar collectors or reflectors that impart the solar energy to water or another working fluid, which undergoes the Rankine cycle and produces electric power in a conventional turbine. Figure 7.5 depicts the essential components of such a solar-thermal power plant, which are:

a) The pump that circulates the working fluid;
b) The system of *solar reflectors* and a *central receiver* that receives the solar energy and raise vapor;
c) The vapor turbine, usually working with steam and
d) The condenser.

It is observed that the components of Fig. 7.5 are identical to those of the simple Rankine cycle of Fig. 3.7 with the exception that the boiler has been substituted by the reflector-receiver combination. It follows that the thermodynamic diagram of this solar powered cycle is identical with the T-s diagram depicted in Fig. 3.8a and the P–v diagram depicted in Fig. 3.8b. Similarly, all the Rankine cycle improvements that have been enumerated in Sect. 3.6.1 may be applied to the solar powered cycle. Typically, the receivers of a solar power plant may produce steam at 550–600°C. Irreversibilities of the practical Rankine cycle cause the cycle efficiencies to be in the range 38–42%. The overall thermal efficiency of the solar plant is significantly lower (20–28%) because of other thermal losses associated with the collection and transmission of solar power. These are enumerated in Sect. 7.2.2.

A variation of the Rankine cycle working with steam is to use another fluid, such as a refrigerant or a hydrocarbon. The choice the Organic Rankine Cycle (ORC) allows the use of lower temperatures, which are usually accompanied by lower efficiencies. It also adds to the cost of construction of the solar power plant.

The operation of the solar thermal power plant cycle is very similar to that of any other small, Rankine cycle, power plant. Steam is raised at high pressure and is directed to the turbine at pressures in the range 10–50 bar temperatures in the range 550–600°C. The turbine and the condenser are located at the foot of the receiver tower and operate in a way that is similar to turbines and condensers of fossil fuel plants. However, cooling water is not always available in locations with high potential for solar thermal power plants. For example, the Southwestern part of the United States and the Saharan countries are excellent regions for solar power production. Both regions are also arid, with very few rivers or natural lakes that could provide enough cooling water to a power plant. For this reason, solar thermal plants are usually designed with dry cooling towers, that is, they are air cooled. As a consequence, their condensers operate at temperatures in the range 50–60°C. This is detrimental to the overall thermal efficiency of the power plants.

Striving for higher cycle efficiency and more power out of a given amount of insolation, engineers have developed several *Stirling Cycle engines* in the first part of the 21st Century. The T,s diagram of the Stirling cycle, which works with air as the working fluid, is shown in Fig. 7.6. Process 1-2 is an isothermal compression of the gas accomplished by a compressor with an embedded heat exchanger. Process 2-3 is an isochoric (constant volume) compression, where the addition of heat increases the pressure of the gas. Process 3-4 is an isothermal expansion in a gas turbine, also embedded with a heat exchanger. Finally, process 4-1 is an isochoric expansion, where the removal of heat causes the depressurization of the gas. A great deal of the heat rejected during the process 4-1 may be transferred to the heat addition process, 2-3 by a heat exchanger, which is called a *regenerator*, thus lowering significantly the overall heat requirements of the cycle.

The four processes of the Stirling cycle may be accomplished in a cylinder-piston engine. A thermodynamic analysis of this cycle shows that its theoretical efficiency is equal to the Carnot efficiency, which is the maximum possible efficiency a thermal engine may achieve:

$$\eta_{St} = \eta_C = \frac{T_3 - T_2}{T_3}. \tag{7.7}$$

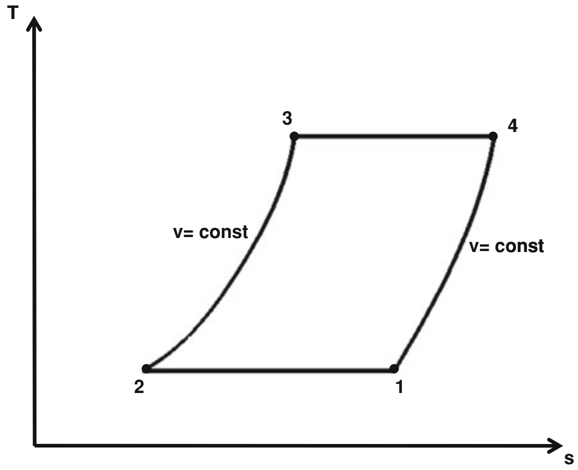



**Fig. 7.6** The T-s diagram of the Stirling cycle

However, practical Stirling engines exhibit efficiencies significantly lower than this upper limit, because of internal cycle irreversibilities. One of the reasons for the lower efficiencies is that the two isothermal processes, 2-3 and 4-1, are difficult to achieve in finite time, because heat diffuses slowly in and out of the gas. In addition, the fouling of the heat transfer surfaces contributes to the quick deterioration of the Stirling engine because it slows more the heat transfer processes. Despite of these limitations, the Stirling cycle has been extensively studied and refined since the 1990s and several engines that operate accordingly have been constructed. As a result of this research, several Stirling engines are now in operation with practical efficiencies in the range 25–35%. Technological advances in this area, which are focused in the areas of almost isothermal compression and expansion, may deliver engines that are more suitable for solar energy utilization.

Figure 7.7 shows an aerial photograph of *Solar Two* a small, 10 MW pilot thermal power plant that was built near Barstow, California. Solar Two resulted from the conversion of a smaller thermal power plant, Solar One, by the addition of several rows of heliostats and was decommissioned in 1999. The receiving tower, the turbine housing building, the solar reflectors and the large area covered by the reflectors of this rather small power plant are visible in the photograph. One of the attractive features of the Solar Two plant was the use of a pool of molten salts (60% $NaNO_3$ and 40% $KNO_3$) as heat storage medium. This allowed the power production to continue normally during brief reductions of insolation due to cloud coverage. It also allowed the plant to produce power up to 3 h after sunset. While the Solar Two power plant was decommissioned, this type of project of solar thermal energy conversion is considered successful: *Solar Tres*, a new, scaled up 15 MW pilot project with energy storage capacity is under construction in Andalucía, Spain.

**Fig. 7.7** An aerial photograph of Solar-Two, a 10 MW solar thermal plant near Barstow California (courtesy of Sandia National Laboratories)

## *7.2.2 Solar Reflectors and Heliostats*

One of the salient characteristics of solar is that it is a diffuse form of energy. This means that the energy density incident on a given area is relatively low, typically less than 1 kW/m$^2$ and, oftentimes, much less. Let us consider a small solar-thermal power plant that produces maximum power[2] of 15 MW with an overall thermal efficiency 25%. We would need approximately 60 MW of heat power for the operation of this plant. A simple calculation shows that even at the maximum rate of incident radiation of 1 kW/m$^2$, we would need at least 60,000 m$^2$ of reflecting area. This area corresponds to a large number of solar reflectors, which must be placed in a predefined pattern with all of them reflecting the Sun's energy to the central receiver.

Ideally, the solar reflectors would be slightly parabolic—in order to direct the solar energy to a point in the solar receiver—but, oftentimes flat reflectors are used because they are less expensive and easier to manufacture. The dimensions of the

[2] Solar thermal power plants are rated based on the maximum power they may deliver. The average power produced by a solar power plant is always significantly less than the rated power.

solar reflectors are squares or rectangles with typically 4–5 $m^2$ reflecting area. Hence, the hypothetical 15 MW electric power plant would utilize a minimum of 12,000 reflectors. Taking into account all the losses and other practical factors, the actual number of reflectors would be closer to 20,000. This implies that a solar thermal power plant would utilize a great deal of land area and also, since the power received depends on the solar insolation of a region, this land area would depend strongly on the region the power plant is built.

The land area required by solar thermal power plants depends on the number of solar collectors that must be placed. Typical solar thermal power plants in the southwest part of the United States utilize 5–6 acres of land per peak MW (2–2.5 ha/MW). Power plants in areas with lower average insolation require significantly more land area.

One of the important considerations for the solar thermal power plants is that the solar energy reflectors may not be left stationary on the ground. As the Sun apparently moves in the sky, each reflector must receive the solar energy and re-direct it precisely at the central receiver. Therefore, the reflecting angle of each receiver must be constantly adjusted to compensate for the apparent motion of the Sun. The process of adjustment of the reflecting angle is called *tracking the Sun* and is accomplished continuously by two methods:

a) Computer control on the reflector side, which orients the reflector surface according to the position of the Sun in the sky
b) Active control with sensors that track the reflected beams so that they are continuously received at particular areas on the central receiver.

Both tracking systems require two degrees of freedom for the effective tracking of the Sun in the azimuthal and elevation directions. In order to minimize the costs of the systems, several reflectors (from 4 to 16) are mounted on the same tracking system. When the reflectors are fitted with tracking systems, their aim is almost constant and directed consistently at the stationary central receiver. For this reason, the reflectors are called *heliostats*[3] and the field where they are positioned, the *heliostat field*. It becomes apparent that the directional control of the heliostats must be precise, or the energy received will not reach the collector. This is a factor that limits the size of the heliostat field and, consequently, of the maximum power of the power plant. Very large solar power plants, e.g. on the order of 400 MW, would require correspondingly very large heliostat fields, where thousands of heliostats must be placed very far from the receiver. Small errors in the controls of the tracking system would result in larger errors in tracking and the loss of a high fraction of the insolation received. Because of this inherent limitation, the size of the solar thermal power plants is limited to a few tens of MW.

[3] “Heliostat” literally means “one that keeps the sun still.” Because the heliostats rotate with the sun, from the point of view of the central receiver the sun remains still at the same point in the horizon.

The cost of the heliostats is a significant part of the cost of the solar power plant and ranges between 30 and 50% of the capital plant's investment. Because of this, it is of interest to design inexpensive heliostats by large-scale manufacturing processes. Other factors that affect the economic considerations of the heliostats are solar reflectivity, durability and environmental impact. Given the enormous size of typical heliostats, the use of lighter but high-strength and highly-reflecting materials is one of the prime factors that come into the design of these devices. The high strength of the materials is necessary for the many-reflector heliostats to withstand the wind drag.[4] The originally used glass materials are gradually substituted with reflecting polymeric films that are coated with very thin silver or copper films, which reflect the incident solar energy well. Light composite materials for the support of the reflectors and thin silver or aluminum reflective films have been tried recently as reflector surfaces. Problems with these newer designs include delamination of the coatings and a gradual deterioration of the composite that results in reflectivity reduction over long periods of Sun exposure.

On the receiver side, two main types of central receivers are used, *cavity and external*. Both types are essentially heat exchangers that receive heat and impart it as enthalpy to the working fluid of the cycle, typically water. The cavity receivers have a few cavities that face outside, and where the power of the heliostats is concentrated. Coolant tubes line the interior of the cavity to absorb the power. The rest of the cavity receiver is enclosed to minimize radiation and reflection losses. In the external receivers, the coolant tubes are on the outside and receive directly the incident power. Both types of receivers are placed on relatively high towers, on the order of 100 m, which enable all or most of the reflected solar energy to reach the receiver. Figure 7.8 depicts a typical arrangement of the tower and heliostat field in the Northern hemisphere, where the Sun provides power from the Southern direction. The dimensions in this figure are based on the height of the receiver tower, $H$. It is observed that most of the heliostat field lies to the North of the receiver, and that the closest heliostats are placed at distance $0.75H$ from the foot of the receiver.

### 7.2.3 Energy Losses and Thermal Power Plant Operation

The physics of solar radiation; the design of the heliostats; the desired compactness of the heliostat field; and the design of the central receiver introduce several energy losses, which are added to the loss of energy from the outer atmosphere to the solar power plant. These additional losses are:

1. *Cosine losses*: because the function of the reflectors is to direct the solar energy to the central receiver, their reflective surfaces are not perpendicular to the Sun rays. Therefore, the incident radiation on the heliostats is reduced by the cosine

[4] Wind is generally stronger in areas that have high insolation, because of the strong ground heating and the natural convection that follows.

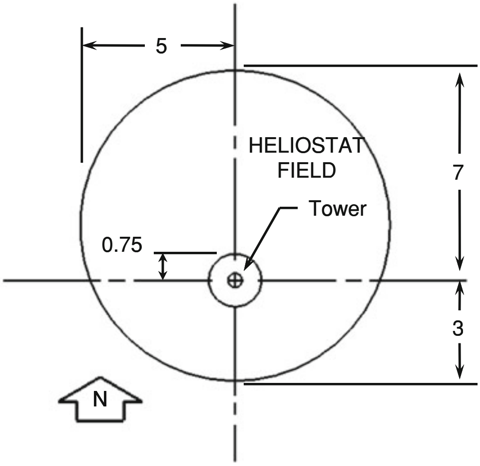



**Fig. 7.8** Typical arrangement of a solar heliostat field and receiver for a power plant in the North hemisphere. All dimensions are based on the height of the central receiver

of the angle that is formed between the Sun's rays and the perpendicular direction of the reflecting surface.

2. *Shadowing*: shadows are cast from the central receiver as well as from one heliostat to another. While the receiver has a relatively small area and its shadowing is not significant, the shadowing from heliostats may become a very important loss of power, especially when the Sun is close to the horizon.
3. *Blocking*: is similar to shadowing and refers to reflected sunlight blocked by other receivers or heliostats.
4. *Reflective losses*: no reflective surface has 100% reflectivity. The surfaces of currently used mirrors reflect between 85 and 95% of the incident solar energy.
5. *Attenuation*: these are the atmospheric losses between the heliostats and the central receiver and are caused by water vapor, particulates and smog in the air between the receiver and the heliostats.

On the receiver end, the most important losses of the reflected solar power are:

1. *Reflection:* the material of the central receiver has a finite reflectivity and, as a consequence, some of the incident radiation is reflected. Painting the surface of the receivers with absorptive paint may minimize the reflection losses to 4–6% of the total power. Cavity receivers have lower reflection losses than external receivers because they "trap" the Sun's rays.
2. *Heat losses at the receiver*, by radiation conduction and convection. The central receivers are essentially heat exchangers that operate at very high surface temperatures to produce high temperature steam. The outside surface temperature of the central receivers is in the range 650–800°C and, because the function of the receiver is to absorb as much of the transferred power as possible, there is no thermal insulation to minimize any heat transfer losses. With external receivers, the heat transfer losses from the receiver may be as

high as 20% of the transmitted power. Cavity receivers have typically lower, but not insignificant, heat transfer losses.

3. *Spillage:* the energy reflected by the heliostats that does not reach the central receiver is the spillage. Spillage is caused by control errors in the tracking system or high winds and may be minimized by the better design of the heliostat controls. A good design of the heliostats would minimize the spillage losses to less than 5% of the total power. The spillage in external receivers is lower than in cavity receivers, which are more compact.

As long as the heliostats aim at the central receiver of the plant, the latter must be supplied with cooling water that raises steam and removes the heat transmitted. Interruptions of the supply of cooling water, or of a similar cooling fluid, would cause the overheating of the central receiver and damages associated with high temperatures. The interruption of cooling water for a few minutes may cause the partial melting of the materials of the receiver and its partial or total destruction. This type of scenario is similar to the Loss of Coolant Accident (LOCA) in nuclear reactors. In order to avoid LOCA accidents an emergency supply of water by fast-activated emergency pumps is a necessary safety system in solar thermal power plants. However, while a LOCA accident in a nuclear power plant may have very adverse environmental consequences, a similar accident in a solar power plant has limited destructive potential and, at worse, is limited to the replacement of the central receiver.

The energy losses at the heliostat and receiver ends are lumped together and appear as the *collection efficiency,* $\eta_c$, of the plant. The collection efficiency is the ratio of the energy absorbed by the working fluid of the thermal solar plant cycle to the insolation energy at the location of the plant. If the collection efficiency of a thermal power plant is 60% and the insolation in the location is 800 W, the working fluid in the cycle receives heat power of 480 W.

Another efficiency of interest is the *overall thermal efficiency* of the plant, $\eta_a$, which is defined as the net electric power produced by the thermal power plant divided by the insolation at the location of the plant. The latter is equal to the product of the collection efficiency and the thermal efficiency of the cycle:

$$\eta_a = \frac{\dot{W}_{\text{net}}}{\dot{W}_{\text{rad}}} = \eta_c \eta_t. \tag{7.8}$$

Typical thermal solar power plants have peak collection efficiencies in the range 50–70% and their Rankine cycles have thermal efficiencies close to 40%. Therefore, the overall thermal efficiencies calculated for peak power of well-designed thermal solar power plants are in the range 20–28%. Given that the power plant does not operate continuously from sunrise to sunset, the time-average overall efficiency of a solar power plant is even lower, in the range 14–22%.

One of the significant limitations of a thermal solar power plant is that it does not operate continuously. Its actual operation is limited by the available solar power, which is periodic and predictable. However, the solar thermal plants do not commence their operation at sunrise and they do not stop operating at sunset when the solar incident radiation approaches zero. Because of the placement pattern of the heliostats and the long shadows, the plant typically operates when the Sun is at least $15^{\circ}$ from the horizon. This limits the hours of operation of the plant to significantly fewer hours than the sunlight hours and, as a consequence, limits the total energy produced by solar power plants. The hours of the daily operation of a thermal solar power plant range from a maximum of 11 h during the summer solstice, to a minimum of 5 or 6 during the winter solstice. Of course these values depend to a great extend on the latitude, where the solar power plant is located.

This is shown in Fig. 7.9, which has been produced with data corresponding to San Antonio, Texas, during the vernal equinox. The data pertain to collection efficiency 60% and overall thermal cycle efficiency 40%. The figure shows the effects of the heliostat and the receiver losses as well as the effect of the finite operation of the power plant. It is apparent in the figure that only a small part of the total incident solar energy is transformed to electric output. In this case the total, daily incident energy on 1 $m^2$ is approximately 18.1 MJ, the energy that is transmitted and becomes available at the collector is 10.9 MJ and the energy produced by the plant during its hours of operation is 3.7 MJ. Thus, only 20.5% of the incident solar energy is converted to electricity by the power plant.

The following conclusions may be drawn from Fig. 7.9 and the discussion of the collection and transformation of solar energy:

1. Because of the inherent losses in the heliostats and central receiver, only 50–60% of the incident solar power is transferred to the working fluid of the thermal cycle.
2. Because the plant does not operate continuously, the total daily thermal energy transmitted to the working fluid of the cycle is 35–50% of the daily solar energy that is incident on a flat surface. The total energy is calculated from the area/integral under the corresponding power curves. This fact, in combination with the thermal efficiency of the solar thermal power plant, which is approximately 35–40%, limits the average overall efficiency of utilization of solar energy to 14–22%, even for the well-designed units. Herein lays the importance of a more efficient thermal cycle for solar plants, such as a well designed and well-functioning Sterling cycle.

This average efficiency, $\eta_{av}$, which is based on the average energy (not power) a solar plant may produce during a period of time, $T$, typically one day or one year is defined by the following expression:

$$\eta_{av} = \frac{\frac{1}{T}\int_0^T \dot{W}_{net} dt}{\frac{1}{T}\int_0^T \dot{W}_{rad} dt} = \frac{1}{T}\int_0^T \eta_c \eta_t dt. \tag{7.9}$$

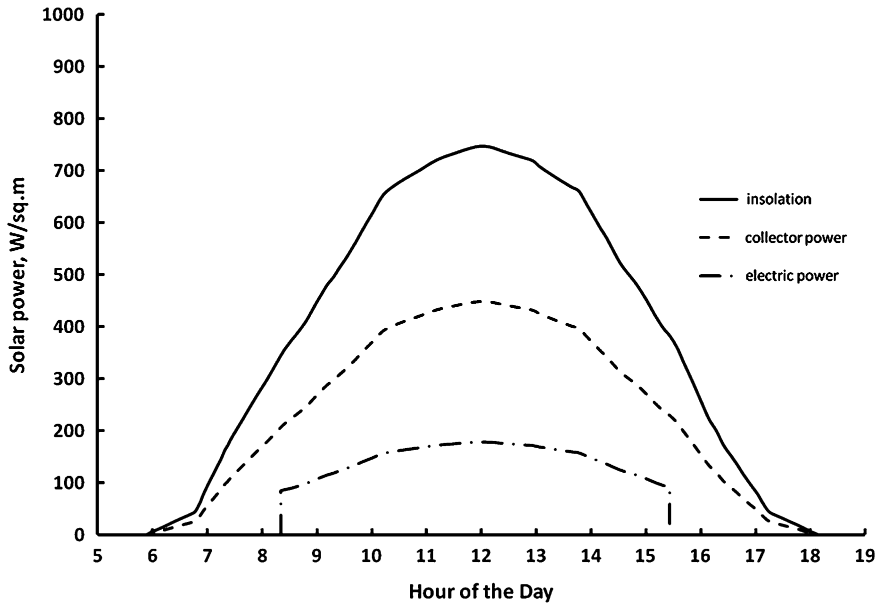



**Fig. 7.9** Normal insolation, hours of operation of a solar thermal power plant, power losses attributed to the heliostats and power losses attributed to the receiver

It must be noted, however, that the thermal efficiency of a solar power plant—as well as the efficiency of most renewable energy power plants—does not have the same meaning as in the case of fossil fuel plants. In fossil fuel plants, the efficiency is a figure of merit that represents the benefit to cost ratio of the plant. The numerator is associated to the revenue that may be derived from the electric energy produced and the denominator in the efficiency expression of fossil power plants essentially represents the cost of the fossil fuel. Solar energy is free of any cost. The operators of solar plants do not pay for the heat received from the Sun, while they receive revenue or other benefits from the energy produced. A better figure of merit for solar and other renewable energy plants is the cost per kWh produced, usually expressed in $/kWh or $/MWh (the US$ would be substituted to the national currency in other countries). The thermal efficiency values may be used for the comparison of two cycles or plant designs or for engineering improvements of a given installation.

Thermal energy storage has been proposed in order to extend the operation of solar thermal power plants and to smooth their power output. Accordingly, some of the steam produced by the solar receiver during peak power would be stored in underground tanks to be used later. Since the steam is to be used within a few hours and the steam tanks can be well insulated, the thermal losses from such a system would be minimal. However, the storage system is still in the planning or feasibility stage of development and there are not any commercial solar thermal power plants that utilize thermal storage.

### 7.2.4 Solar Ponds

The concept of the solar ponds combines power production from solar energy and storage. A solar pond is essentially a pool of water, approximately 1 m deep. In a typical pool the water is heated by the Sun and rises to the surface, where it partly evaporates. The evaporation of the water vents a great deal of the pool's water as vapor; does not allow the accumulation of a great deal of energy in the pool; and keeps the average temperature of the water to low levels. Actually, the temperature of a typical pool in the summer is low enough for it to be used for recreational activities.

If the natural convection process that brings warmer fluid to the pool surface is suppressed, it is possible for the water temperature at the bottom of the pool to increase significantly by absorbing solar radiation. This may be accomplished in a salt-gradient solar pond, which uses natural salt (NaCl) as well as transparent partitions to suppress the natural convection in the pool. The depth of the solar pond is approximately 1 m and its bottom and walls are coated with a light absorbing material. The water in the solar pond is usually separated in three layers:

a) The bottom layer is saturated with salt and, therefore, its density is significantly greater than the density of pure water
b) The intermediate layer, which also contains salt at lower concentration, and
c) The upper layer, which is pure water without any salt.

Even though some solar ponds do not have partitions between the three layers, it is advisable to include transparent partitions in order to suppress molecular diffusion, which will disturb and annihilate the salt gradient.

When sunlight enters the solar pond, it is captured by the absorbing bottom and walls as well as the water. The temperature of the water close to the bottom rises, but the density of the salty water in this layer is high enough for natural convection to not occur. The transparent partitions between the three layers create a "greenhouse effect," thus trapping an additional quantity of heat in the two bottom layers. A great deal of the insolation absorbed remains at the bottom of the pond, where the temperature rises significantly. Temperatures as high as 95°C have been recorded in the bottom layer of well-designed solar ponds. Temperatures of this magnitude are sufficient to produce vapor in a suitable secondary fluid, such as pentane, butane or a refrigerant, which becomes the working fluid of a Rankine cycle operating with the solar pond as the boiler. Figure 7.10, depicts schematically the operation of a Rankine cycle powered by a solar pond. The thermodynamic states of this cycle and the equipment used are similar to those of the solar thermal power plant of Fig. 7.5 and that of the basic Rankine cycle, which was depicted of Figs. 3.7, 3.8a and 3.8b. The two main differences of the cycle, which is suitable with a solar pond, are:

a) The working fluid is a suitable fluid with lower boiling point and
b) The solar pond, which stores thermal energy, has substituted the boiler of the Rankine cycle.

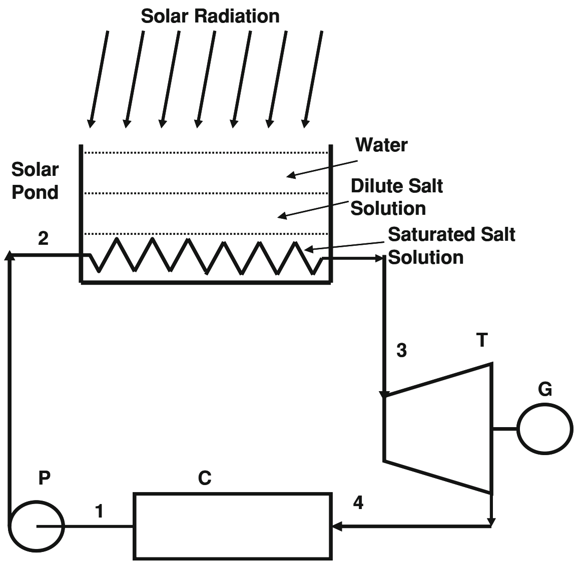



**Fig. 7.10** A Rankine cycle operating with a solar pond as heater

Another characteristic of solar ponds is that, because their area is limited to a few hundred m$^2$, the corresponding power plants are very small, with power ratings on the order of a few hundred kW.

It has been recommended that the water from the uppermost layer of the solar pond be used for the cooling system of the small power plant. While this is possible, it is not advisable because: a) charging and discharging the upper layer of the pond would create waves that increase the reflectivity of the pond and also the water advection would accelerate the diffusion of the salt solution to the upper layers of the pond; and b) the uppermost water layer becomes warmer from conduction and, hence, has higher temperature than ambient water. Given that the upper temperature of the cycle associated with a solar pond is approximately 90°C, even a small increase of the cooling water temperature will have a significant and detrimental effect on the overall efficiency of the cycle. For this reason, if another source of water is available, it is highly recommended that it be used for cooling.

Because the water has very high heat capacity, a solar pond may store a significant amount of energy to be used when the Sun is low in the horizon. The production of electricity from a solar pond may continue even in the evening hours, when there is no natural insolation, thus providing a good alternative to produce power in the evening hours, when the demand is high because of air-conditioning needs. The main advantage of solar ponds is that they serve simultaneously as electric power generating plants as well as storage media.

The disadvantage of solar ponds is that they loose a significant amount of heat to the ground and to the atmospheric air. Because of this, the temperature of the lower zone becomes high enough to produce power for only a limited period of time during the year, typically for a few weeks during the summer. Even during these weeks, the solar pond temperature drops during the nights to levels that do not support power generation. Therefore the energy efficiency of solar ponds—defined as the electric energy produced during a year divided by the total incident solar energy—is expected to be very low. This energy efficiency was calculated to be 0.28% for a solar pond operating in San Antonio, Texas under the weather conditions prevailing in this City. The temperature of this solar pond was high enough to produce power between June 2 and August 31 of a typical year. The pond typically produced power for a few hours during these days from noon to early evening. The temperature and energy absorbed during the daylight hours were not high enough for power to be produced during the night, when stored energy is needed for electricity generation. Clearly, a solar thermal power plant is a better alternative for the production of electric power than a solar pond.

### 7.2.5 Passive Solar Heating: Solar Collectors

The most widespread use of solar energy is the passive heating of buildings and water. While passive heating does not produce electricity or any other form of energy, it helps avoid the use of fossil fuels or electric power for heating purposes and, thus, helps conserve the energy resources of the planet.

Passive solar heating in buildings is caused by an artificial *greenhouse effect:* Glass and several polymeric materials allow low-wavelength solar radiation to pass through them, but trap high-wavelength radiation. These materials effectively act as high-wavelength radiation filters. An enclosure that is covered by one of the greenhouse materials and faces the Sun "traps" a great deal of the solar energy. As a consequence, the temperature inside the enclosure will rise. Thermodynamic equilibrium between the enclosure and its surroundings will be established when the heat transfer from the enclosure—via conduction and advection—is equal to the difference of the radiation energy that enters and exits the enclosure. A simple piece of glass placed on the top of an otherwise open water tank, which is exposed to the Sun in the southern European countries, would raise the temperature of the water by 15–25°C. This is an adequate temperature for the water to be used in domestic applications. Well-insulated enclosures may reach temperatures 40–50°C higher than the ambient. Such enclosures are called *solar collectors* or simply *collectors*. The solar collectors are typically placed on the roofs of buildings, facing the prevailing direction of the Sun—south in the northern hemisphere and north in the southern hemisphere—and are used for water and space heating.

A schematic diagram of the cross-section of a solar collector is depicted in Fig. 7.11. Because a typical collector is placed on a roof, the solar collector depicted is at an angle with the horizontal. The inside material of the collector is coated with absorbing paint and usually has a dark color. Solar energy enters the top of the collector through the double glass and heats up the enclosed fluid, which is typically water or a solution. Depending on the design of the collector, the

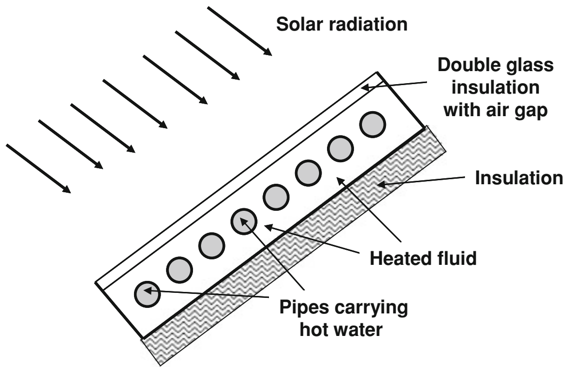



**Fig. 7.11** A solar collector placed on a rooftop

temperature of this fluid may reach 70–85°C. Another, closed water circuit picks up the heat from the collector and dissipates it inside the building: the water that is circulated through the pipes of this circuit may supply the tank of a water heater and maintain it at the typically required temperature of 45–50°C, or it may circulate via space heaters to supply the heat required to maintain a comfortable condition in the building.

Solar collectors may trap direct or diffuse solar radiation. Because they also absorb diffused radiation, they may operate even in the cloudy autumn and winter days when most of the heating for the buildings is needed. Since the heated water may be stored for later use, the solar heating of buildings is not limited only to the daylight hours and may extend into the night hours. With the appropriate design of the heating system, solar heating may provide hot water and heat for buildings throughout the year and save a significant amount of primary energy resources.

Because of reflections at the outside surface of the collector and the incident angles, which are not 90°, the amount of radiation that enters the solar collector is less than the local solar insolation. This deficit in power entering the collector may be accounted by a radiation-loss factor, $\beta_r$. If the temperature of the enclosure is denoted by $T_{en}$, and that of the ambient is $T_{amb}$, and the useful heat extracted from the collector is $\dot{Q}$, the following energy balance equation applies at the steady-state operation of the solar collector:

$$\beta_r \dot{W}_{rad} = UA(T_{en} - T_{amb}) + \dot{Q}, \tag{7.10}$$

where $U$ is the overall heat transfer coefficient of the collector and $A$ its area. A well-designed collector has sufficient insulation to not lose any heat from the bottom and its sides. Therefore, the area $A$ is the area exposed to the Sun.

The efficiency of the solar collectors is defined as the heat power removed by the water circuit to the insolation at the location of the collector:

$$\eta = \frac{\dot{Q}}{\dot{W}_{rad}} = \beta_r - \frac{U(T_{en} - T_{amb})}{\left(\dot{W}_{rad}/A\right)}. \tag{7.11}$$

In the southwest part of the USA typical values of the peak insolation are 900 W/m$^2$. With typical overall heat transfer coefficients $U = 4.5$ W/m$^2$K, radiation-loss factors, $\beta_r = 0.82$ and temperatures $T_{en} = 60$°C and $T_{amb}$=25°C, collector efficiencies may reach 65%. Because of the ambient temperature variations, solar collector efficiencies become lower during the winter months and higher during the summer.

The maximum temperature a collector may attain is when there is no heat removal, that is when $\dot{Q} \rightarrow 0$. From Eq. (7.10), the maximum temperature for the enclosure is:

$$T_{en}^{\max} = T_{amb} + \frac{\beta_r \left( \dot{W}_{rad}/A \right)}{U}. \tag{7.12}$$

Depending on the location of the collector and the type of insulation it has, the maximum temperature in the enclosure may reach 150–200°C. For example, with the values given in the previous paragraph for collectors in the southwestern part of the USA, the maximum temperature the collector may reach under typical weather conditions would be $T_{en}^{max} = 189$ °C. Since the collector enclosure without heat removal is a closed system, an internal temperature increase of this magnitude would result in steam formation, pressurization and damage to the enclosure. When designing solar collectors, it is important to incorporate safety systems for the enclosed fluid not to vaporize and for the internal pressure not to exceed values that would damage the collector.

Among the other uses of passive solar energy for households is solar cooking by *solar stoves*. This is typically accomplished with solar energy concentrators: when solar energy is concentrated in enclosures similar to those used as solar collectors, the temperature may rise significantly to reach the levels needed for the preparation of meals. The temperatures of solar stoves are regulated in a precise manner by allowing some of the internal fluid to evaporate or vent. Several of these solar stoves are being marketed successfully throughout the world.

An often neglected form of solar energy usage is clothes drying. Despite the fact that it is not continuously used, a clothes dryer consumes 5–6% of the total household energy in the USA. Drying the clothes under the Sun would save on the average 5–6% of the total energy used by households. However, in the USA there are several homeowners associations that have regulations against the solar drying of clothes for "aesthetic reasons." Similar regulations and behavioral norms exist in many other OECD countries. National, regional or local policies that ban such energy-wasting regulations would result in significant energy savings in the households by using a higher fraction of the free, passive solar heating.

It is apparent that most if not all of the heating needs of households may be provided by passive solar heating. Well-designed solar collector systems may supply heat and hot water to the households throughout the year. Cooking and clothes drying may also be accomplished with solar energy. The wider application of passive solar heating in households worldwide will reduce significantly the use of natural gas and other hydrocarbons and will save these natural energy resources for other uses.

## 7.3 Direct Solar-Electric Energy Conversion: Photovoltaics

*Photovoltaic cells* or *solar cells* convert the energy of the Sun directly to electricity. A product of the space race, the solar cell has been successfully used since the 1950s to power satellites, the International Space Station as well as remote terrestrial locations far from the electric grid. Because of the abundance of solar energy on the planet, the potential of photovoltaic devices to produce electric energy is immense: With maximum incident solar power density on the Earth's surface of approximately 1 kW/m$^2$, a few square meters of solar cells combined with energy storage for nighttime use, may provide the entire need of electricity for several households. Solar cells potentially may supply the entire energy needs of humanity, including thermal and electric energy. Since the Sun will always shine in the foreseeable future, photovoltaic devices with appropriate storage methods (see Chap. 12) have the potential to supply the energy demand of the Earth's population for millennia. Despite the advances in the manufacturing of solar cells, in the beginning of the twenty-first century, electricity from photovoltaic devices is still more expensive to produce than electricity from fossil fuel power plants.

Two developments in the early part of the twenty-first century may help shrink the price gap between photovoltaic and fossil fuel produced power: The fossil fuels are being depleted at a fast rate, causing their prices to increase and, at the same time new knowledge in materials science and technological advances are applied to photovoltaics, thus, causing the price of solar cells to decrease. With the two developments continuously occurring, there may be a point in the future when electricity produced by photovoltaic devices will be first competitive and then cheaper than electricity produced by other means. Because of the wide fluctuations and unpredictability of prices, we will examine the methods and technical merits of photovoltaic energy conversion without any reference to prices and economics.

### *7.3.1 Band Theory of Electrons*

It is known from fundamental physics and chemistry that atomic nuclei are surrounded by electrons that move around the nuclei in well-defined orbits. The electrons have distinct energies and are subjected to the *Pauli Exclusion Principle,* which stipulates that two electrons may not exist in the same atom unless their states are different. Electrons in isolated atoms may exist in certain *levels of energy,* which are sharply defined. However, in groups of atoms, such as in crystals where atoms are arranged closely together and electrons interact with

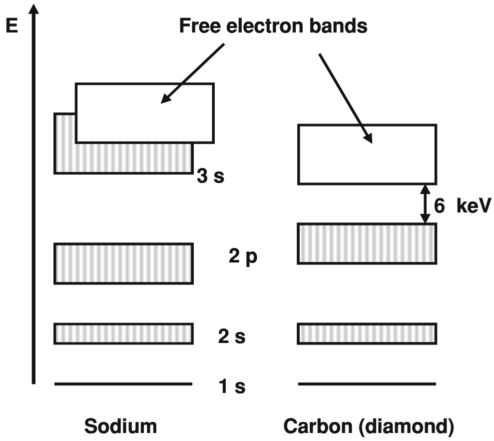


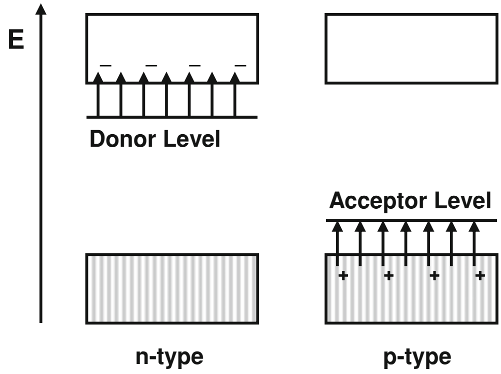

**Fig. 7.12** Electron bands for a metal (sodium) and a non-metal (diamond)

several nuclei, these energy levels are not sharp and become energy bands, which are significantly wider for the outer electrons of an atom. The Pauli principle applies and excludes electrons from existing in the energy levels between the bands. These energy levels are sometimes called *forbidden bands.* At the upper end of electron energies there is a continuous band where electrons may exist as *free electrons.*

The free electrons are shared by the entire crystal and do not belong to specific atoms or nuclei. In metallic crystals the free electron band overlaps with the band, which is at the immediately lower level. In insulators, the free electron band is separated from its immediately lower band by a significantly high forbidden band. This is depicted in Fig. 7.12, where the bands of sodium and carbon (diamond) are shown in a schematic diagram. Because the free electron band in sodium overlaps with the immediately lower *3s band*, the outer electrons of sodium may easily become free electrons and be shared by the entire metallic crystal. From a microscopic point of view, the metallic crystal looks like atoms in a structured arrangement that exist in a sea of free electrons. An applied voltage would provide the motive force to support the movement of the free electrons of metals, thus, causing an electric current to pass through the metal. However, the forbidden gap of 6 eV in the outer electrons of the diamond is high enough not to allow a significant number of electrons to become free electrons. As a result, diamond and similar non-metallic elements do not conduct well electricity and heat. They are electric (and heat) insulators.

There is a type of materials, the *semiconductors,* where the energy gap between the free electron band and the immediately lower band is small enough, typically between 0.5 and 1.4 MeV. At low temperatures, semiconductors do not have a large number of free electrons and behave as insulators. However, at higher temperatures the thermal energy of the electrons is sufficiently high to enable a significant number of electrons to cross the last forbidden band, to become free electrons and to allow the material to conduct electricity and heat.

**Fig. 7.13** Electron energy bands for n-type and p-type semiconductors




The transition of a semiconductor to a conducting material is facilitated by the addition of a small amount of an *impurity,* which creates an allowed energy level in the last forbidden band. This process is called *doping* and typical concentrations of the impurity are in the range $10^{-5}$–$10^{-6}$ (a few parts per million). Depending on the position of this allowed energy level, electrons from this energy level may "jump" into the free electron band. In this case, the conducting free electron band has a surplus of electrons, the semiconductor is called *n-type* and the new energy level is a *donor level.* Alternatively, electrons from the last valence band may "jump" onto the new energy level, which is called an *acceptor level.* The last valence band has a deficit of electrons or a surplus of "holes" for electrons and the semiconductor is called *p-type.* The electronic processes that create the n-type and p-type of semiconductors are depicted schematically in Fig. 7.13, where the symbols + and − denote the created electric charges that are caused by the jumping of electrons from one band or level to another.

With the addition of impurities, electrons may become excited and cross the small energy gap even at room temperatures. Crystalline silicon (Si) of very high purity is the typical semiconductor base material. Common doping/impurities materials are boron for the creation of the n-type and arsenic for the creation of the p-type semiconductors. In both types of semiconductors, the acceptance or donation of electrons by the impurity atoms creates charges in the valence level or free electron bands in the atoms of the semiconductor. This phenomenon is exploited in a *solar cell* or *photovoltaic cell (PV cell)* for the production of electric power.

## *7.3.2 Solar Cells and Direct Energy Conversion*

When a layer of a p-type semiconductor comes in contact with a layer of a n-type semiconductor, the charged valence and free electron bands create a voltage difference across the combined material, which is called the *n-p junction.* If the

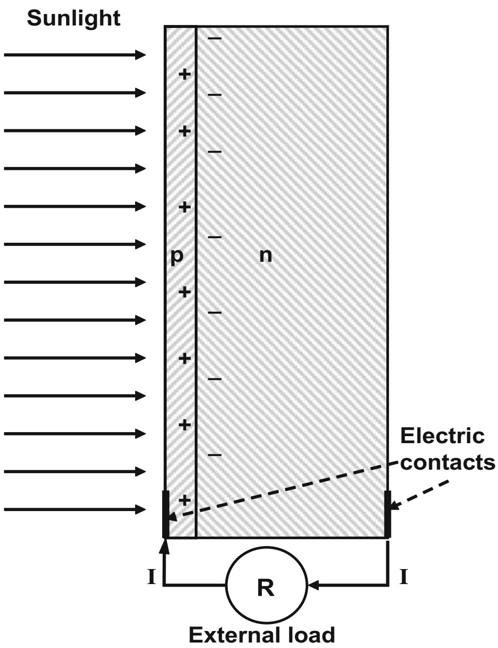



**Fig. 7.14** The p-n junction and the production of electric power

opposite ends of the n-p junction are connected by an external electric circuit, electric current will flow until the electric balance of the valence and free electron bands is restored. In the absence of a mechanism or process that would continuously excite electrons from the donor or acceptor level to the valence or free electron bands respectively, the electric charge equilibrium will be soon established in the p-n junction and the electric current will stop.

The continuous excitation of electrons, which maintains the voltage difference across the p-n junction, is accomplished by the sunlight in the *solar or photovoltaic cell.* This is essentially a p-n junction and is shown in Fig. 7.14. The solar cell is composed of a very thin film of a p-type semiconductor joined with a significantly thicker layer of n-type semiconductor. Typically, the p-type film is on the order of 1 μm and the n-type layer is on the order of 1,000 μm. The incident sunlight penetrates the entire part of the p-type film, enters and partly penetrates the n-type material. The photons in the sunlight cause the excitation of electrons in both types of semiconductors: in the p-type film, electrons jump from the valence band to the acceptor level, while in the n-type layer, electrons jump from the donor level to the free electron band. Oftentimes, this process is described as the *creation of electron-hole pairs* close to the p-n junction.

The charge imbalance close to the p-n junction causes the diffusion of electrons from the n-type side to the p-type side of the solar cell. This creates a shortage of electrons in the n-type side and a surplus in the p-type side. The outer electric contact on the n-type side becomes a positive electrode and the outer electric contact on the p-type side becomes a negative electrode as shown in Fig. 7.14. This causes the current, $I$, to flow as shown in the figure, in a direction that is opposite to the flow of electrons. The continuous insolation on the surface of the p-n junction, creates continuously electron–hole pairs near the junction, maintains the voltage difference across the electrodes and, hence, provides continuous power to the external electric circuit. The higher the insolation power, the more electron-hole pairs are produced and the more power the solar cell produces.

It is apparent from Fig. 7.14 that the conversion of the solar radiation power to electric power occurs as a result of the electric material properties of the p-n junction. Furthermore, the conversion occurs directly from electromagnetic radiation to the electric potential created in the p-n junction, to electric power. Apparently, during the conversion process there is no significant thermal energy generated and, more importantly, there is no conversion of thermal energy to electric power. This process is called *Direct Energy Conversion (DEC).* A significant advantage of the DEC is that it is not subjected to the Carnot efficiency limitation (Eq. 3.22), which limits the efficiency of thermal engines. Because it is not limited, in principle the efficiency of a DEC engine/device may be as high as 100%. However, the current materials technology in the current and the projected generations of solar cells exhibit significantly lower conversion efficiencies for reasons that will be explained in the next section.

The voltage, current and power supplied to the electric load of Fig. 7.14 depend on the resistance of the external load, $R$. When $R$ is very high and the circuit is almost open, the voltage developed by the cell is maximum, $V_o$. This maximum voltage, $V_o$, is a monotonically increasing function of the insolation, $\dot{W}_{rad}/A$, and reaches a plateau at high values of the insolation. At the other extreme, when $R$ is very low, the cell is short-circuited, the current is a maximum at $I_{ss}$ and the voltage developed by the cell almost vanishes. The short-circuit current, $I_{ss}$, is a linear function of the insolation. Figure 7.15a shows the typical variations of the open-circuit voltage and the short-circuit current for solar cells. The power produced by the solar cell is equal to the product of the voltage and current developed in the external circuit and depends on the external resistance $R$. By varying $R$ between the two limits of open circuit and short-circuit, where the power produced is zero, one obtains the characteristic curves of a solar cell, which are depicted in Fig. 15b for two values of the insolation, $\dot{W}_{rad}/A$. It is easy to show from algebraic considerations that, under constant insolation, the maximum power is produced at the point where the slope of the tangent to the corresponding characteristic curve is equal to $-1$.

### *7.3.3 Efficiency of Solar Cells*

As with all the electromagnetic waves and radiation, light may be considered as a wave or as a flux of individual particles. The light of different wavelengths is

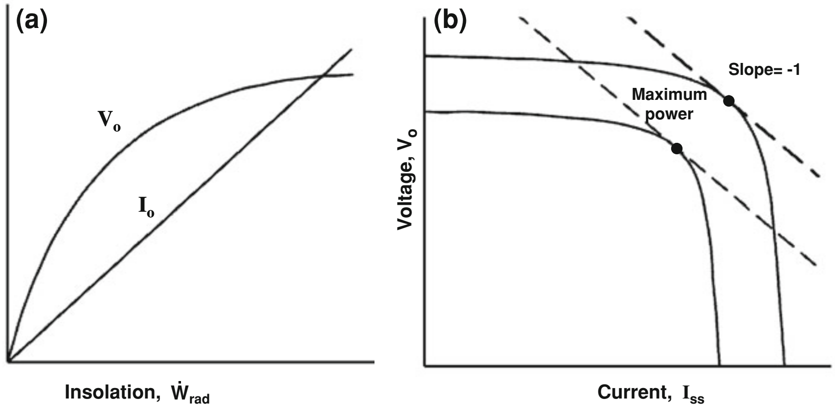



**Fig. 7.15** **a** Typical variation of the open-circuit voltage and short-circuit current with insolation **b** Two characteristic curves and maximum power of a solar cell

considered to be transmitted by a stream of light-carrying particles, called *photons,* which possess momentum and energy. The energy carried by photons is a function of their frequency:

$$E = h\nu = h\frac{c}{\lambda}, \tag{7.13}$$

where $h$ is Planck's constant, equal to $6.6256*10^{-34}$ Js; $\nu$ is the frequency of the light; $\lambda$ is the wavelength of light; and $c$ is the speed of light in vacuum, which is equal to $3*10^8$ m/s.

Of importance in calculations on photovoltaics is the number flux of photons, $\varphi_p$, which is incident on a given surface. Since the solar radiation is composed of a range of wavelengths, as shown in Fig. 7.2, there is also a range of photon energies that represent the solar spectrum. The energy of the average photon outside the Earth's atmosphere is approximately 1.48 eV. Given the value of the solar constant, S = 1.353 kW/m$^2$, the average number of photons that are incident on a surface of 1 m$^2$ at the outer end of the atmosphere is $5.8*10^{21}$ photons/(s-m$^2$). Therefore, a photovoltaic cell with area 45 cm$^2$, placed at the limit of the atmosphere and perpendicular to the rays of the Sun, would receive on average $2.6*10^{19}$ photons/s.

The photons interact with the structure of the photovoltaic p-n junction, and create the electron-hole pairs that are necessary for the development of the electric voltage. However, not all the photons have the energy or the capacity to create an electron–hole pair. Photons with low energies (high wavelengths) do not have enough energy to cause the needed "jump" of an electron from the donor level to the free electron band and are ineffective in producing electricity. On the other end of the spectrum, a photon may only create a single electron–hole pair, which entails a small amount of electric energy. Photons with very high energy, that is

**Table 7.1** Photon characteristics and conversion to electric energy (data from El-Wakil 1984)

| Frequency range (Hz) | Wavelength range (μm) | % of solar energy | Fraction converted | % Energy converted |
|---|---|---|---|---|
| $<2.72*10^{14}$ | >1.1 | 22 | 0 | 0 |
| $3.33–2.72*10^{14}$ | 0.9–1.1 | 13 | 0.91 | 12 |
| $4.29–3.33*10^{14}$ | 0.7–0.9 | 20 | 0.73 | 15 |
| $6.00–4.29*10^{14}$ | 0.5–0.7 | 28 | 0.55 | 15 |
| $10.00–6.00*10^{14}$ | 0.3–0.5 | 17 | 0.36 | 5 |
| $>10*10^{14}$ | <0.3 | 0 | 0 | 0 |

high frequency or low wavelength, do not have the capacity to create more than one electron-hole pairs and, hence, a great deal of the energy of these photons is not used for the production of electric power. The excess energy of these photons is dissipated as heat on the solar cell. Table 7.1 shows the frequency, wavelength and energy carried by the photons, and the fraction of the energy that may be converted to electric energy in a semiconductor photovoltaic cell. One may conclude by adding the numbers of the last column of the Table that, under ideal conditions, only 47% of the incident sunlight radiation may be converted to electric energy.

The efficiency of a solar cell is defined as the ratio of the electric power it produces to the total insolation. It is apparent from this Table, that the reason for the low theoretical efficiency of semiconductor PV cells is the significant mismatch between the incident solar radiation and the capacity of the cell to convert the radiation to electricity. A "solar filter" that would convert the frequency of the entire solar radiation to an equal amount of energy with photons in the frequency range $4.29*10^{14}$ to $2.72*10^{14}$ Hz would be ideal. Such a filter would increase the theoretical conversion efficiency of photovoltaic solar cells to levels closer to 80%.

While crystalline silicon solar cells have been used for decades and have an excellent performance and reliability records, their production entails a great deal of energy input, because pure crystalline silicon requires a great deal of energy to be produced. Typically, the production of a PV cell requires four to five years of the energy it produces. This and the associated labor costs make photovoltaic energy appreciably more expensive than energy from conventional power units and are an impediment in the reduction of the production costs of silicon solar cells. More recent photovoltaic technologies have focused on the production of less expensive semiconductor materials regardless of the conversion efficiency. One such method is to deposit amorphous (e.g. non-crystalline) semiconductor materials, onto very thin film substrates of lower cost.

Thin film technology makes use of cadmium telluride (CdTe) or copper indium gallium selenide (CoInGaSe or CIGS), and amorphous silicon. The most recent designs of this technology strive to achieve the higher possible solar cell efficiency with thin films by using strategically chosen combinations of materials (multi-junction cells) and single materials (full spectrum cells) that respond to wider ranges of the available solar spectrum in a region, thereby producing more power.

A second method is to concentrate on the technology for the production of less expensive solar cells by using more common and less pure materials, regardless of the efficiency that is achieved. For example, thin film polymeric solar cells have been produced with gallium arsenide as the doping. These cells have lower efficiencies (6–8%) but significantly lower production cost. Such low efficiencies are acceptable because the input energy, the insolation, is free of charge. For the more widespread use of energy from photovoltaics, the technology will have to concentrate mainly on two factors:

a) Lower energy costs, which will have to be reduced to less than $0.1/kWh;
b) Storage methods for the energy to become available during the nighttime and the winter months.

### *7.3.4 A Futuristic Concept: The Space Solar Power Station*

The two principal disadvantages of the terrestrial use of solar energy are:

1. The insolation at a given terrestrial location is highly variable, because of the Earth's rotation around the Sun and
2. Because of the atmospheric absorption there is significant power attenuation from the outer atmosphere to any given location as shown in Fig. 7.2.

Both of these terrestrial effects are absent outside the atmosphere of the Earth, where a solar receiver may be placed and its orbit designed so that the carrier satellite remains outside the shadow of the Earth. Such a receiver, which may be called a Space Solar Power Station (SSPS), will always face the Sun and will be capable to produce electricity continuously, because the Sun will always be in sight. Given the atmospheric attenuation losses and the periodic fluctuations of insolation, which are associated with the location of the terrestrial solar power plants, the SSPS will be capable to produce between 4 and 5 times more energy than an equivalent terrestrial power plant.

Of course, all the electricity produced in the space will have to be transported to the Earth in order to be used by the population. Microwave transmission systems have been proposed for this purpose. Accordingly, a SSPS would consist of very large solar panels that always face the Sun and a transmission antenna that continuously converts the electric power to microwave radiation and transmits it to a receiving station on the surface of the Earth. In this location the microwaves would be converted back to electric energy and will be distributed to the markets of electricity. In order to minimize atmospheric absorption, reflection and scattering a suitable microwave frequency, e.g. below 10 GHz, may be chosen for the transmission of the power. Clouds, rain, and hail may have some impact on the transmission by absorbing or scattering some of the energy transmitted. These effects may also be minimized by an optimum choice of the transmission frequency and the location of the receiving antenna.

The SSPS concept has received significant attention as a viable method for the utilization of solar energy, but an actual pilot plant has not been built yet. Some of the problems associated with the SSPS concept are:

1. The transportation of material to a space orbit, which requires significant amounts of energy by itself.
2. The effect of the transmitted microwaves on airplane traffic, birds and other animals in the path of the microwave radiation.
3. Interference with communication frequencies.
4. Biological effects on humans from the scattering of this radiation.
5. The significant cost of the producing and receiving stations and the unknowns associated with their operation, which implies a significant economic risk.

Given the inherent scientific and energy advantages of the SSPS concept, its potential to supply significant amounts of energy continuously to a fixed location (or locations) on Earth and the absence of storage requirements, this method of electricity production appears to be promising. While there are several serious impediments for its implementation at present, it is currently technologically feasible and may become economically feasible and advantageous in the future, when advances in materials science and propulsion will make the transportation of efficient photovoltaic cells to an orbit more commonplace and less expensive.

## 7.4 Environmental Issues of Solar Energy Utilization

Solar energy is one of the most benign forms of alternative energy. Its current utilization, either as solar-thermal or as photovoltaic conversion, causes very few environmental concerns. The principal environmental advantage of solar energy is that its utilization does not involve chemical or nuclear reactions. Thus, no chemical emissions (e.g. carbon dioxide, $NO_x$ gases, etc.) and no radionuclides are emitted from a solar energy facility. This makes solar conversion an environmentally friendly energy source.

The most significant environmental impact of solar energy is associated with the production of the materials that comprise the photovoltaic cells. Silicon, germanium and phosphorous are produced and purified with the consumption of significant amounts of energy and involve the use of polluting chemicals such as sulfuric acid and cyanide. However, all the pollution associated with the production of solar cells is localized and contained at the production facility. The pollution at large production sites may be very well regulated and assurances may be given that all hazardous chemicals used for the production of solar cells will not be released to the environment. A more significant concern in the production of the photovoltaic cells is the high amount of energy consumed during their manufacturing process. Currently, the energy consumed for the manufacturing of a silicon-based solar cell is equivalent to the energy the cell will produce in approximately 4 years. Leaner manufacturing methods and different cells made of new materials may reduce this significant energy requirement.

Thermal pollution is associated with all solar energy operations. Solar thermal power plants reject a significant amount of heat in their condenser. Similarly, photovoltaic arrays reject all the incident radiation that is not converted to electricity. The heat power (waste heat) rejected by a plant, which produces electric power $\dot{W}$, with an overall efficiency $\eta$ is given by the expression:

$$\dot{Q}_{rej} = \dot{W}\frac{1-\eta}{\eta}. \tag{7.14}$$

A 100 MW thermal power plant operating with 40% thermal efficiency would reject 150 MW of heat and a 1 kW solar panel array with an efficiency of 20% would reject a total of 4 kW of heat. Because solar installations occupy a larger area than similar fossil fuel installations, the waste heat is dissipated over significantly larger areas and does not have the same adverse impact on the environment. Also, the fact that solar installations are, in general, located in remote, often deserted, areas, the thermal pollution caused by such installations seldom affects the human population and becomes unnoticed. Associated with the thermal pollution is the water use, if the solar plant is cooled by water. The amount of water used by such a solar thermal power plant is approximately the same as the water used by a thermal power plant, which rejects the same amount of heat power.

Land use is another environmental effect of solar energy utilization. Solar energy is diffuse and, hence, the production of significant amounts of it requires a large land area, which is significantly more than the area used by a thermal power plant, fossil or nuclear. For this reason, inexpensive, unutilized and usually deserted areas have been chosen for the location of solar energy facilities.

A notable beneficial environmental effect of solar energy that is utilized in urban environments, e.g. photovoltaic panels or passive solar panel heating on the sides and rooftops of buildings, is that some of the incident solar radiation is utilized inside the buildings and, therefore, it is not absorbed, but reflected back to the atmosphere or scattered. Considering the overall energy balance in the vicinity of the buildings, the solar energy systems produce a small but important cooling effect in the urban environment, which results in slightly lower ambient temperatures and reduces the need for building air-conditioning.

## Problems

1. What is the mass rate of the Sun, in kg/s, which is converted into solar power? Hint: use the first statement in this chapter.
2. The solar collectors of a spacecraft that orbits the Earth have an area 42 m$^2$. What is the solar energy these collectors absorb in 3 h?

3. Using Eq. (7.1) prove *Wien's law*, that the wavelength at the maximum of the radiation spectrum of a black body is given by the relationship: $\lambda_{max}T = 0.0029$ mK.
4. Using Fig. 7.4 determine what is the annually averaged energy, in kWh, absorbed by a 10 $m^2$ solar collectors in the following locations: a) Hannover, Germany; b) London, England; c) Timbuktu, Mali; d) Calcutta, India; e) Buenos Aires, Argentina.
5. Photovoltaic cells with an overall average conversion efficiency of 10% and total area of 5 $m^2$ are placed in the following locations: a) Hannover, Germany; b) London, England; c) Timbuktu, Mali; d) Calcutta, India; e) Buenos Aires, Argentina and f) New York, USA. Determine the total amount of electricity, in kWh, produced annually in each location.
6. At a certain location, the average insolation on a flat plate collector is 7,200 kJ/($m^2$*day). Such a solar collector is used to continuously provide 38,000 Btu/hr or heat to a process. If the collector efficiency is 42%, what should be the area of the collector?
7. It has been suggested that refrigerant R-134 be used instead of water for a new type of thermal solar collector. What is your opinion on this? Explain in detail your reasoning.
8. A thermal solar power plant uses 1,300 heliostats, each one with an area 25 $m^2$. The annually averaged peak insolation in the area is 700 W/$m^2$. The thermal solar energy collection efficiency of the plant is 56% and the efficiency of the cycle is 38%. Determine the annually averaged peak power produced by this power plant.
9. The drag force on a surface due to the wind flow is given by the expression:

$$F_D = \frac{1}{2}A\rho C_D V^2, \text{ with } C_D = \frac{24}{\text{Re}}\left(1 + 0.32\text{Re}^{0.687}\right) \text{ and } \text{Re} = \frac{\rho L V}{\mu} \tag{7.15}$$

where $V$ is the velocity normal to the surface; $C_D$ is the drag coefficient; Re is the Reynolds number; and $L$ is a characteristic dimension, which is equal to the square root of the area of the collector. A is the area that is perpendicular to the wind direction. A circular solar collector is placed at an angle 30° to the horizontal and has a diameter $d = 7$ m. The wind flows in the horizontal direction. Make a diagram of the drag force on the collector versus the wind velocity, when the latter varies in the range 0–72 miles per hour. What do you observe?
10. A 20 MW (peak) thermal solar power plant is to be built in a region where the annually averaged peak insolation is 640 W. Because of high wind currents in the region, the area of the heliostats is not to exceed 12 $m^2$. If the overall thermal efficiency of the power plant is 18%, calculate the number of heliostats that must be constructed for the plant.
11. A 10 MW (peak) solar power plant is proposed for the Dallas, Texas region. At peak power, the overall efficiency of the plant is estimated to be 21%. Determine the minimum area of the heliostats that must be used for this plant.

12. Use typical values in your locality to calculate the solar collector efficiencies. Also, calculate what would be the maximum temperature the fluid in the collector may reach and suggest methods to keep the internal temperature below 90°C.
13. What is the energy of photons with wavelength 20, 50, 100, 200 and 800 nm?
14. A solar cell only converts the photons in the range $2.72*10^{14}$ to $4.29*10^{14}$ Hz. The efficiency of this photon conversion is uniform and equal to 58%. What is the maximum efficiency this solar cell will have?
15. "We have the know-how and the capability to produce a 60% efficient solar cell, but we lack the investment to produce it commercially." Comment on this statement by writing a 250–300 word essay.
16. A solar filter has been invented that would convert all the photons of the solar spectrum, which have frequency less than $2.72*10^{14}$ Hz, to photons of frequency $3.2*10^{14}$ Hz. The total number of photons will not change. Calculate the improvement on the maximum efficiency of the semiconductor solar cells this filter will cause.
17. A SSPS is rated to produce 20 GW of electric power and transmit it to the Earth via a microwave guide. The solar cells cover 85% of the total area of the SSPS. If the SSPS is of square shape and, if it faces the Sun directly, calculate the total area of the SSPS. You may assume that the solar cells in this station have maximum efficiency.
18. "The Sun is producing abundant and free energy that may be used to meet economically the entire energy need of this country, but the petroleum cartel undermines all efforts to do that." Comment on this statement by writing a 350–400 word essay.