# SOLAR HEATING

The world's supply of fossil fuels is finite and is expected to be depleted in the foreseeable future. Though nuclear energy systems are not similarly constrained, particularly since the development of breeder reactors, nuclear waste problems still remain unresolved. The future of fusion technology, where the fuel is essentially unlimited, is also uncertain at the present time. As a result, there is a great potential for alternative renewable energy sources, such as solar energy.

Humankind has a very long history of solar energy utilization dating back to prehistoric times. The total solar radiation incident on the surface of the earth is on the order of 80 trillion kW, which is more than 10,000 times the annual global energy consumption for all human activities at present (1). Although energy availability is not an issue, its direct use is constrained by three factors: (1) the low energy flux (a maximum of about 1 $kW/m^2$); (2) the large variations and unpredictability of the incident terrestrial radiation due to localized weather conditions; and (3) the need to convert the energy to forms that are more easily transported/stored (e.g., electricity, chemical fuels). These increase the overall cost of energy obtained from solar radiation, so that solar energy systems are uneconomical for most large-scale industrial and commercial applications.

In spite of these limitations, direct solar heating systems have become more acceptable, and in many cases, commercially viable because of the increasing economic and environmental costs of energy. This is particularly true for many low temperature applications (<100°C to 150°C), such as water and space (i.e., building) heating and industrial processes, such as distillation, salt/brine production, and drying. A number of other applications, such as cooking, power generation, cooling/air conditioning, and detoxification/disinfection have also been investigated over the years. Most of these are still in the developmental phase though a few designs have been commercialized to a limited extent.

The applications of direct solar heating applications are quite diverse. However, the basic design in all cases is determined by three factors:

- the availability of solar energy at a given location
- the energy collection and storage requirements
- the end use of the energy as related to the actual application

Issues relevant to each of these are discussed separately in the following sections.

## SOLAR RADIATION AND ITS DISTRIBUTION

### Background

The solar constant $G_o$, defined as the energy flux (or irradiance) incident on a surface perpendicular to the incoming solar radiation outside the atmosphere of the earth at the mean earth–sun distance, has been measured by numerous researchers. Based on a range of satellite and other measurements, the estimated value of the solar constant is 1366 $W/m^2 \pm 3\ W/m^2$ (2), corresponding to an equivalent blackbody temperature of about 5780 K. Spectral analyses show that about 98% of this energy lies between the wavelengths of 0.3 $\mu$m and 4.0 $\mu$m. Seasonal variations in the irradiance due to the elliptical orbit of the earth are on the order of ±3%. Additional fluctuations caused by sunspot activities over its approximately 11 year cycle are believed to be less than 1.5%.

For engineering applications, the solar constant is assumed to be fixed even though small changes have been recorded in addition to the normal variations described. This assumption has no impact on solar system design because the energy incident on the surface of the earth differs significantly from the solar constant. Scattering effects are caused by air molecules (Rayleigh scattering, mostly at wavelengths below 0.6 $\mu$m) and by dust/water particles (Mie scattering). In addition, absorption by ozone, water vapor, and carbon dioxide has a strong impact on the overall transmission of radiation through the atmosphere. As a result, the wavelengths of interest for terrestrial applications are limited to the region between 0.29 $\mu$m and 2.5 $\mu$m (Fig. 1, see Ref. 3).

Terrestrial solar radiation consists of beam (i.e., direct) and diffuse components. Limited experimental studies suggest that the spectral distributions of both components of radiation are very similar, though the diffuse component is shifted slightly toward the shorter wavelengths because of higher scattering in this region. The actual spectral distribution and energy content of radiation at any given location are ultimately determined by three factors related to the scattering and absorption processes. These include the "air mass," a

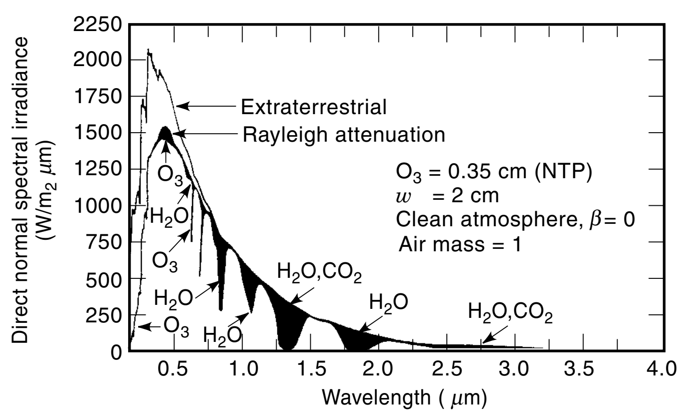


**Figure 1.** Extraterrestrial solar radiation and the effects of Rayleigh scattering and atmospheric absorption on the spectral distribution of beam irradiance (From J. A. Duffie and W. A. Beckman, in *Solar Engineering of Thermal Processes,* Wiley, 1991. With permission.)

measure of the length of the radiation path in the atmosphere, the precipitable water content, and the dust content of the atmosphere.

### Measurements of Solar Radiation

A knowledge of the amount of solar radiation received at a given location surface is essential for the design, evaluation, and optimization of solar thermal systems. Thus, instruments based on photovoltaic detectors have been developed to measure the duration of bright sunshine. Similarly, instruments to measure the direct solar radiation flux (pyrheliometers or actinometers) and the diffuse and total solar radiation fluxes (pyranometers or solarimeters) are also available. More recently, extensive work has been done to develop satellite-based techniques for measuring solar insolation over large areas (4).

Standard and secondary standards pyrheliometers use a comparator-type approach where the incident radiant energy is compared with a known heat input. These devices are difficult to use in practice, and operational devices are usually based on direct temperature measurements using multijunction thermopiles. Before use, these field instruments must be calibrated, and when carefully used, errors with well-calibrated instruments of this type are quite small (on the order of 5% or less), though thin clouds or haze may increase errors to as much as 10% or more.

Pyranometers also use thermopile detectors and are calibrated against standard pyrheliometers, though they may be occasionally calibrated against secondary standard pyranometers. Alternative pyranometer designs are based on bimetallic strip transducers or photovoltaic detectors. Though the spectral response of a silicon cell differs from the typical solar spectrum, errors introduced by this difference are believed to be less than 5%. However, it is important to note that the errors may be much larger if reflected radiation from the surroundings is a significant fraction of the total incident radiation.

The diffuse component of the radiation is measured with pyranometers modified to include a shading ring. In this case, correction terms on the order of 5% to 20% are usually necessary because the ring shades the detector from some of the diffuse radiation (in addition to the direct component). Measurements of radiation on inclined surfaces are also made with conventional pyranometers. However, the measurements may need to be corrected by as much as 10%, depending on the instrument used.

### Estimates of Solar Radiation

Solar radiation data required for systems design are often unavailable. Thus, the average incident radiation is often estimated from empirical equations developed for this purpose. These were originally of the following form (5):

$$\frac{H}{H_c} = a + b\frac{n}{N} \tag{1}$$

where $H$ is the irradiation on a horizontal surface, (i.e., the energy incident per unit area integrated over a specific time period e.g., year, month) where the subscript $c$ refers to a "clear sky" terrestrial value, $n$ is the daily number of hours of bright sunshine averaged over the duration under consideration, and $N$ the average length of the day.

The clear sky irradiation $H_c$ required in this correlation can be estimated from equations relating the terrestrial normal irradiance $G_c$ (including the effects of latitude, longitude, altitude, and climate type) to the extraterrestrial value $G_o$ (6). The average length of the day $N$ can be easily evaluated because it is a direct function of the solar constant, the orbital position of the earth around the sun during the time period of interest, and the actual geographic location (latitude and longitude) under consideration. The parameter $n$ and the empirical constants $a$, $b$ have been obtained from regression analyses of solar radiation data for various locations around the world and are available in literature. For areas where these values are unavailable, suitable estimates are obtained by using data from locations with similar geographic and climatic conditions.

In recent years, a number of other models/equations for estimating the solar radiation have been developed. Many of these involve the clearness or cloudiness index $H/H_o$ ($H_o$ being the extraterrestrial irradiance), which helps eliminate the parameter $H_c$ from the calculations. In the simplest cases, these equations may be based on simple linear regression analyses, as described previously. Other equations are based on another parameter, the average cloud cover $C$, which is derived from empirical data or from more complex models. Considerable research in this area is continuing at present (7).

## ENERGY COLLECTION AND STORAGE

A critical part of any solar thermal system is the collector which is designed to absorb solar energy incident on it. These are often used with energy storage systems because the energy demands for most applications are time-varying and are rarely correlated with the available solar energy. Various types of collectors and storage devices have been developed for different applications. These devices and practical issues surrounding their use are discussed in the following sections.

### Preliminaries

Collectors are classified into two broad categories, nonconcentrating or flat-plate collectors and concentrator-receiver-type collectors. In either case, it is first necessary to estimate the solar radiation incident on their surfaces before designing a solar thermal system. For a horizontal surface, methods for estimating the incident energy have already been discussed in the previous section. For inclined surfaces, the problem is more complicated, and the beam and diffuse components of the incident radiation must be considered separately.

**Radiation on Inclined Surfaces.** The beam component of radiation is obtained directly from the sun. Thus, it can be evaluated from geometric considerations once the angles relative to the horizontal plane are known. Any specular reflection from the ground or the surroundings can also be similarly calculated as long as the reflecting surface locations/configurations are well defined. The diffuse component is more difficult to evaluate because a nonhorizontal surface receives radiation by scattering from the sky and by (diffuse) reflection from the ground. Further complications arise because the diffuse component from the sky consists of three separate components, isotropic diffusion which is independent of the direction, circumsolar diffusion which is concentrated in the solid angle region surrounding the sun, and the horizontal brightening effect which is seen near the horizon.

Various models have been developed to account for different components of diffuse radiation incident on inclined surfaces (8). Simple approximations assume that the overall diffuse radiation, including both sky and ground reflected radiation, is isotropic. In such a model, the diffuse radiation is independent of direction, and only the beam radiation geometric effects are important in evaluating the total incident radiation. An improved model, the diffuse isotropic model, neglects anisotropic scattering effects (i.e., the circumsolar diffusion and the horizon brightening) but considers the ground reflection separately and assumes that it is isotropic. Thus, corrections based on radiation shape factors are used to account separately for the energy received from the sky and the ground. Many more advanced models considering the anisotropic scattering effects have also been developed in recent years. Nevertheless, the diffuse isotropic model, which gives conservative results, is still widely used because it is relatively easy to implement.

### Flat-Plate Collectors

A solar collector is a heat exchanger that collects thermal energy in the form of radiation and transfers it to a working fluid. Flat-plate collectors are usually designed to be stationary (i.e., nontracking), and their orientation is selected to optimize the average system performance during the year (or portion of the year). In general, they are classified into two broad categories, air heaters or liquid-plate collectors, depending on the heat transfer fluid. Though the physical configuration of the two types of collectors is somewhat different, the design principles are similar.

A simple liquid collector shown in Fig. 2 consists of a "black" solar energy absorbing surface to which are attached a number of fluid conduits. The conduits are mounted in an enclosure with transparent cover(s) which transmit incoming solar radiation while reducing heat losses from the upper surface. Liquid collectors are typically designed to have selective surfaces with high absorption at wavelengths below 2.5 $\mu$m and low emittances above 3 $\mu$m (for a surface at 200°C, 99% of the emitted blackbody radiation is at wavelengths greater than 3 $\mu$m). This ensures that a very high fraction of the incident radiation is absorbed and the energy emitted is relatively low. The overall enclosure is also well insulated at the rear to further minimize any heat losses to the surroundings.

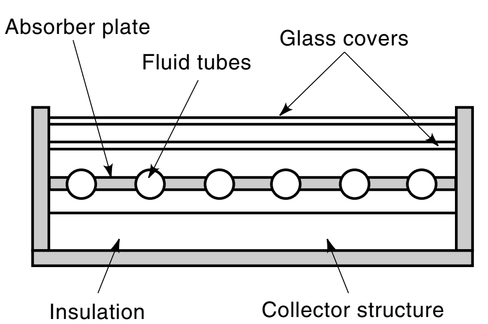


**Figure 2.** Schematic of a simple liquid solar collector.

**Design Considerations.** In an actual collector, the radiation incident on the collector surface is not entirely absorbed by the absorber plate because of some absorption/reflection at the glass surface(s) and some reflection at the plate itself. Though this can be calculated from the transmittance of the glass cover and the absorptance of the absorber plate, it is convenient to define an effective transmittance-absorption product $(\tau\alpha)_{\text{eff}}$ combining the effects of the absorber plate-glass cover combination. In most collectors this is approximated by the expression

$$(\tau\alpha)_{\text{eff}} \approx 1.01 - 1.02(\tau\alpha) \tag{2}$$

where $\alpha$ and $\tau$ are the absorptance of the absorber plate and the transmittance of the glass covers, respectively. Though these must include both spectral and directional effects, hemispherical, total values are typically used because of lack of adequate information, particularly related to directional properties.

Three parameters are of importance in collector design. The collector loss coefficient $U_L$ is the overall heat transfer coefficient summing up the effects of convective and radiative heat losses from the absorber plate:

$$Q = A_c[S - U_L(T_p - T_a)] \tag{3}$$

where $Q$ is the energy gain of the collector, $S$ is the incident radiation absorbed by the absorber per unit area, $T_p$ is the mean temperature of the absorber plate, and $T_a$ is the ambient temperature. The collector loss coefficient can be calculated from a 1-D (or network type) analysis including the individual (conductive, convective, and radiative) heat transfer resistances.

Because $T_p$ is not known a priori and is somewhat difficult to evaluate, it is convenient to define a second parameter, namely, the heat removal factor $F_R$, a measure of the "heat exchanger effectiveness" of the collector. $F_R$ is the ratio of the actual heat transfer to the maximum heat transfer (that would occur if the fluid temperature remained constant):

$$F_R = \frac{Q}{A_c[S - U_L(T_i - T_a)]} \tag{4}$$

where $T_i$ is the inlet fluid temperature. Because the temperature of the fluid is always lower than the temperature of the absorber plate, $F_R$ is less than (or equal to) the collector efficiency factor $F'$. $F'$ is defined as the ratio of the fluid-to-ambient heat transfer coefficient $U_o$ to the plate-to-ambient (i.e., the collector loss) heat transfer coefficient $U_L$:

$$F' = \frac{U_o}{U_L} \tag{5}$$

Then the mean plate and fluid temperatures are related to the previous three parameters as follows:

$$T_f = T_i + \frac{Q/A_c}{F_R U_L}\left(1 - \frac{F_R}{F'}\right) \tag{6}$$

$$T_P = T_i + \frac{Q/A_c}{F_R U_L}(1 - F_R) \tag{7}$$

**Practical Considerations.** In a practical system, the collector performance is affected by a number of factors that are difficult to quantify. Limited experiments suggest that dust deposition on the collector cover plate reduces the energy absorbed by 1% to 2%. Shading effects are also significant, but these can be evaluated only on a case-by-case basis. Shading by the structure of the collector itself can reduce the incident energy. In most cases these are expected to be on the order of 1% to 3%.

Most analyses related to solar collectors assume that a steady-state condition exists as has been done in the previous equations. In reality, a solar thermal system, and particularly the collector, is a transiently operated device. Two effects are important here, the early morning heating of the system and the transient (and often intermittent) nature of the daily solar radiation. Thus, time-dependent models for solar collectors have also been developed and are sometimes used for detailed analysis. In most cases, however, the effects of variations in ambient temperature, wind speed, and solar insolation are relatively small and are neglected in system design.

**Performance Testing.** Performance standards have been developed for solar collectors as their commercial market has increased in recent years. Three parameters are used to characterize the collector performance: the instantaneous collector efficiency, incident angle modifier, and the time constant. The first is a measure of the energy absorbed by the collector relative to the energy incident on it:

$$\eta = \frac{Q}{A_c G} \tag{8}$$

where $\eta$ is the instantaneous efficiency. The second parameter, the incident angle modifier $K\tau\alpha$ gives the effect of the orientation of the collector with respect to the normal direction:

$$K_{\tau\alpha} = \frac{(\tau\alpha)}{(\tau\alpha)_n} = 1 + b_o\left(\frac{1}{\cos\theta} - 1\right) \tag{9}$$

where $b_o$ is the incident angle modifier coefficient. This empirically determined constant is obtained from tests with the collector at different orientations with respect to the incoming radiation. The final parameter, the time constant, is a measure of the heat capacity of the collector and is defined as the time required for the temperature of the fluid to change by a factor of 0.632 (= 1 − 1/$e$) relative to the ultimate steady-state value.

### Concentrator-Receiver Collectors

Concentrator-receiver collectors consist of two components, a reflecting or refractive surface known as the concentrator (9), which is used to direct incident solar radiation to the second component, the receiver. Because of the higher costs of lenses, particularly for larger sizes, most large systems use mirror-type concentrators. These range from simple diffuse back-reflectors (a slight modification of conventional flat-plate collectors), to systems using minimal tracking, nonimaging concentrators, to fully tracking, imaging-type parabolic or Fresnel concentrators or large arrays of heliostats.

The receiver itself includes the absorber, related structural hardware, and thermal insulation. Like a flat-plate collector, the absorber is equivalent to a heat exchanger that transfers the redirected radiant energy to the working fluid flowing through it. Because of the concentration effects, however, the temperature of the working fluid can be raised to much higher values than possible with flat-plate collectors. Thus, most absorbers include vacuum barriers of various forms (Fig. 3) to minimize convective heat losses which are proportional to the temperature difference between the absorber plate and the surroundings. With a smaller absorber area relative to the collector (i.e., concentrator) area, these are therefore quite low in well-designed concentrator-receiver systems.

**Design Considerations.** As in flat-plate collectors, the parameters of importance for a concentrator–receiver collector include the loss coefficient, the efficiency factor, and the heat removal factor. However, two additional parameters, the concentration ratio and intercept factor, are also important in this case. The first is usually based on area and is defined as

$$C = \frac{A_a}{A_r} \tag{10}$$

where $A_a$ is the aperture area (i.e., the projected area of the concentrator) and $A_r$ is the receiver area. This is a measure of the energy concentration whose maximum values are given by

$$\begin{aligned} C_{\text{circ,max}} &= \frac{1}{\sin^2\theta_s} \approx 45,000 \\ C_{\text{lin,max}} &= \frac{1}{\sin\theta_s} \approx 212 \end{aligned} \tag{11}$$

where the subscripts circ and lin refer to circular and linear concentrators, respectively, and $\theta_s$ is the half-angle subtended by the sun as viewed from the earth (≈0.27°). The intercept factor $\gamma$ of a concentrator is the fraction of the radiation incident on the concentrator that is ultimately reflected onto the

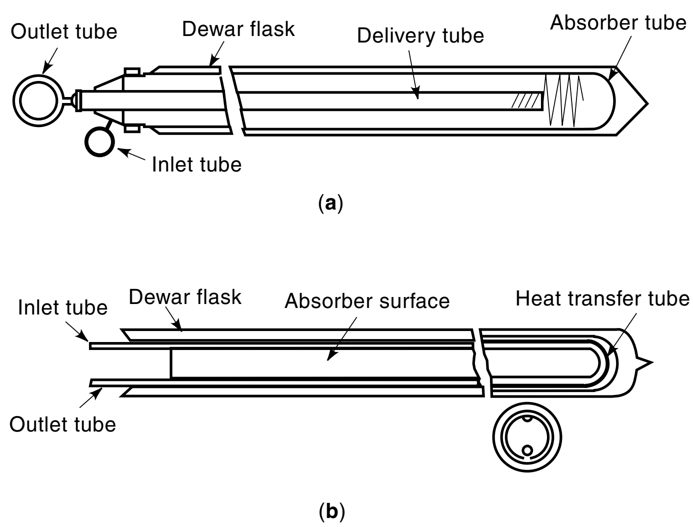


**Figure 3.** Two types of evacuated Dewar tubes with cylindrical absorbers. (a) Dewar with delivery tube. (b) Dewar with inserted fin and tube (From J. A. Duffie and W. A. Beckman, in *Solar Engineering of Thermal Processes,* Wiley, 1991. With permission.)

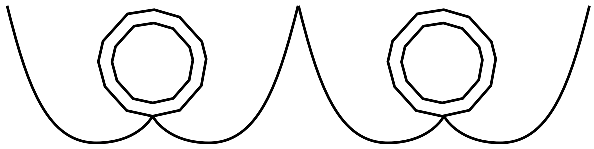

**Figure 4.** Compound parabolic concentrators with cylindrical absorbers.

receiver. In most concentrator–receiver collectors, this is greater than 0.9.

**Practical Considerations.** Concentrator–receiver designs are driven primarily by the beam component of the radiation, except for systems with low concentration ratios ($\leq$10 approximately, e.g., diffuse back-reflector-type collectors). To reduce or minimize tracking requirements, however, nonimaging concentrators have been designed to reflect radiation to the receiver over a wide range of incident angles. For flat receivers, compound parabolic concentrators are commonly used, but involute reflectors provide better performance for cylindrical absorbers (Fig. 4). The large acceptance angle of nonimaging concentrators means that a fraction of the diffuse radiation is also collected by such reflectors.

Parabolic or paraboloidal mirrors (or lenses) are used as concentrators in imaging systems. For a perfect mirror in perfect alignment, linear or circular images are obtained at the focal point. Imperfect reflectors and/or alignment results in an image larger than those expected in the perfect configuration. Thus, the concentration ratios of practical systems must be lower than those of theoretically perfect designs. These effects are particularly evident in linear concentrator-receiver collectors where tracking is typically possible only in one plane. As a result, the image size can vary significantly through the day, depending on the system orientation (E–W, N–S, etc.).

Conventional mirror-based approaches are inadequate for large solar thermal systems designed for power generation or similar processes. For these applications, the system configuration typically includes a central tower-mounted receiver together with a field of independently controlled plane mirrors (heliostats) which direct the solar radiation onto the absorber. Such a heliostat configuration is equivalent to a large Fresnel mirror and provides enormous flexibility in system design. A number of such systems have been tested worldwide.

### Energy Storage Systems

The availability of solar energy rarely coincides with energy demand for a given application because of the obvious transient nature of solar radiation and the time constant associated with all solar thermal systems. To increase the applicability of solar thermal systems, these are often used with energy storage subsystems which store thermal energy when excess energy is available.

Three basic types of thermal energy storage systems have been considered (10). In sensible-heat, thermal energy storage systems, heat is transferred to an energy storage medium with a consequent rise in its temperature. Typical storage media include water in an insulated tank and rocks in a packed-bed configuration. Special designs include storage walls for buildings or aquifier storage for seasonal applications.

In phase-change energy storage systems, the storage medium undergoes a change of phase during the heat absorption/release process. Because of latent heat effects, energy absorption and release occur at a more uniform temperature and the size/mass of the energy storage unit can be reduced significantly.

Chemical energy storage systems are based on reversible chemical reactions. Common approaches are based on decomposition of metal oxides, dehydration of metal hydroxides, and photochemical decomposition. As in phase-change type systems, the energy storage density can be increased significantly. Both phase-change and chemical energy systems are limited by the cost of the storage material(s) and often by material compatibility and related issues.

### Combined Collector-Storage Systems

**Solar Ponds.** The most widely used combined collector-storage system is a solar pond. Solar ponds are 1 m to 3 m deep, large bodies of water in which convection is suppressed by increasing the salinity at the bottom of the pond or by using honeycomb membranes or polymer gels. By minimizing convection, energy absorbed by the bottom layers of water can be stored for extended periods of time because heat losses by conduction at the pond edges and through the upper layers of water are relatively small. As a result, a strong temperature inversion (with bottom temperatures as high as 70°C to 80°C) exists within a well-designed solar pond.

Experimental studies show that as much as 95% of the solar energy in the wavelength region of 0.3 $\mu$m to 0.6 $\mu$m is absorbed in the lower layers of a solar pond when the incident radiation is approximately normal to the pond surface. Radiation at higher wavelengths is absorbed in the upper regions and may not provide usable energy. Heat is removed from the pond by heat exchangers submerged within the pond or by extracting hot water from the lower layers and returning it after use. In the second approach, special care must be taken to avoid destratification and to maintain the stability of the pond.

Saline ponds with salt concentrations increasing with depth are the most common type of solar ponds. The concentration gradients in these solar ponds result in continuous diffusion of salt from the lower layers to the upper layers. To maintain the temperature and salinity gradients in the pond, it is therefore essential to add salt to the lower layers and dilute the upper layers as required. Water evaporating from the pond surface must also be replaced continuously. To minimize wind-induced mixing, wave barriers in the form of nets or pipes are often necessary, particularly for larger ponds. To improve long-term performance, the ponds are lined with membrane liners and/or layers of clay so that leakage is kept to a minimum.

**Collectors With Integral Storage.** On a smaller scale, conventional solar collectors have also been designed with integral storage to simplify the overall system. Such integrated systems have been developed for flat-plate and concentrator-receiver configurations. These may be entirely passive devices, in which water, the heat transfer fluid, may be stored in the collector itself. In other configurations, the storage subsystem may be incorporated in the lower section of the collector/receiver, below the absorber plate, so that the operating temperature of the system is more uniform.

## ENERGY CONVERSION AND UTILIZATION

Solar thermal energy has been used for numerous applications over the years. The most common are residential/commercial water and space (building) heating systems. In addition, solar energy has also been used for cooking and a range of industrial and process applications, such as distillation, salt/brine production, drying, detoxification, power generation, and absorption cooling. These are discussed further here.

### Residential Water Heating

Water heating is probably the most common solar heating application. A typical configuration of a residential water heating system is shown in Fig. 5. Residential water heating systems are of two basic types, natural circulation and forced circulation. In natural circulation systems, density differences due to the temperature rise of the fluid in the collector(s) induces a flow in the system. Because this driving force depends on the heat absorbed, natural circulation systems are self-adjusting to a certain extent. The temperature rise in the collector is about 10°C over a wide range of operating conditions.

In forced convection systems, a separate collector-side heat transfer loop is often employed, and a separate pump transports the heat transfer fluid in this loop. With this approach, it is possible to use a heat transfer fluid other than water. This is particularly advantageous in regions subject to freezing because then antifreeze mixtures (ethylene glycol–water, propylene glycol–water) or air can be used in the collector loop. Furthermore, because the boiling point of antifreeze mixtures is higher than that of water, such systems can also be designed to operate at higher temperatures without increasing the system pressure.

Freeze protection is an important issue for solar water heaters in many parts of the world. If antifreeze mixtures cannot be used because of cost or other constraints, systems may be designed so that the water can be drained back to the tank or out of the system below a set temperature. Alternatively warm water can be circulated through the collectors, if freezing temperatures are rare. Systems can also be designed with risers and headers made of special materials so that they can withstand occasional freezing.

Auxiliary heating is almost inevitably required in solar water heaters. This is true even in the most ideal geographic locations because of the mismatch between available energy and demand. Auxiliary heat is usually supplied by a conventional heater that provides the energy required either in the storage tank, to the water leaving the tank, or to a separate bypass, as required.

A number of specialized solar water heating systems have been proposed over the years. One example is the hybrid solar collector, which converts incident solar energy to both thermal and electrical energy. The electrical energy generated can be used to drive the pump or fan to circulate the fluid in the collector system or for other purposes. Another example is the low flow rate, forced-convection system that has been developed to obtain increased stratification in the storage tank. Such a design provides higher performance at significantly lower cost.

A second large residential application of solar energy is swimming pool heating. The general requirements of this application are similar to those of water heating, though there are a few significant differences. The most important of these is the set-point temperature which is relatively low for a swimming pool. On the other hand, the total thermal energy required is usually much larger than that for a residential water heating system because the mass of water is much greater. As a result, the simplest approach is to use the pool itself as the collector by covering it with a solar transparent (and IR opaque) plastic cover. Alternatively, separate collectors are used in series with the pool pump to heat the water as required.

### Space (Building) Heating

Building (residential or commercial) heating systems are of three general types: passive, active, and hybrid systems. In passive "solar houses," building elements are designed so that individual components also absorb, store, and release thermal energy as required. In one approach, the building may include collector-storage walls that absorb and store incident radiation. In such a design, glazing is put on part of the south wall and the wall itself is painted black (i.e., with a solar radiation absorbent paint). To maximize energy storage, the wall is

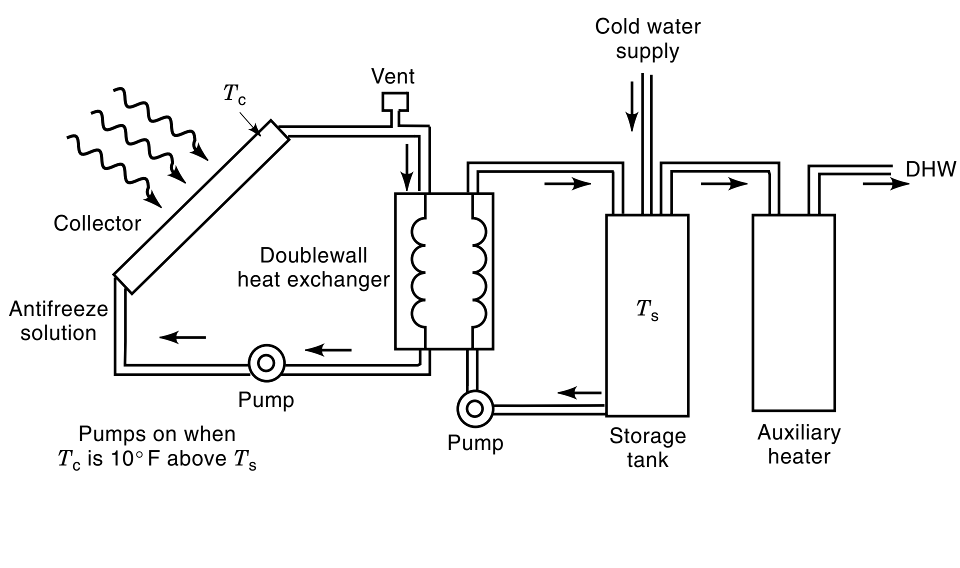


**Figure 5.** A typical residential water heating system.

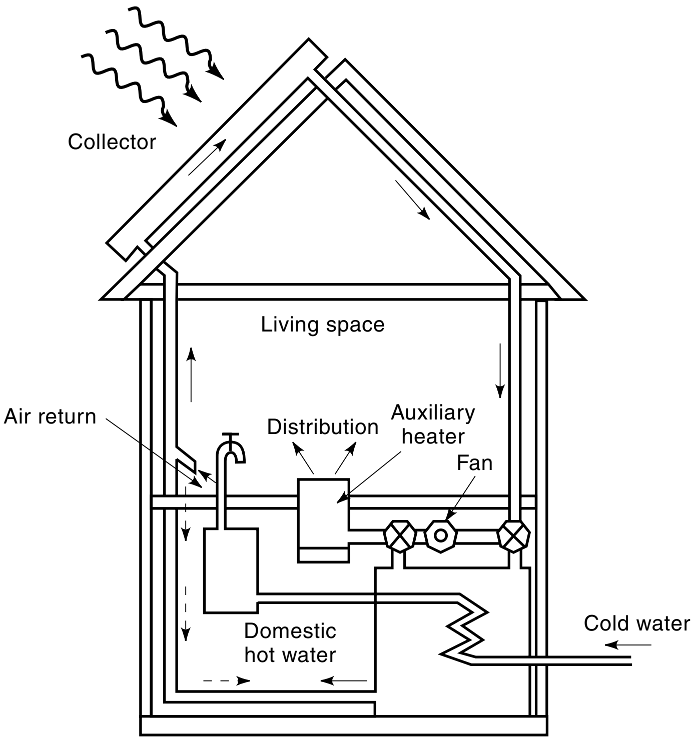


**Figure 6.** A schematic of an active building heating system.

made of masonry or includes a water tank. Absorbed/stored energy is transferred to the living space by forced or natural convection depending on the building design. If necessary, movable insulations, such as screens, shutters, or special plastic foam insulations, are used to prevent heat losses during periods of low solar insolation.

A second approach is to use direct-gain south windows in combination with overhangs and movable insulations. In this case, the room itself is the collector, and the window acts as the glazing material. Alternatively, a greenhouse (or conservatory), which is a glaze-enclosed extension of the house, can be used both as a living space and as a collector. Energy is stored by selecting appropriate materials for the floor and select (interior) walls. Various types of overhangs are used together with passive systems to control the incident radiation on the "collector" surface. Heat distribution is a particularly important issue in passively heated buildings, and therefore architectural design is very important to ensure that proper comfort conditions are maintained.

Active building heating systems are very similar in concept to water heating systems (Fig. 6). Air or water (or antifreeze mixtures) are the typical heat transfer fluids. Liquid-based systems include a closed liquid loop from which heat is transferred to the air via a suitable heat exchanger. Systems using air collectors may be direct or include a separate loop similar to liquid-based systems. If necessary, an energy storage system may be included in either case. As in water heating systems, auxiliary heating is typically required as are freeze/boiling protection systems and suitable controls to maintain the required set points.

An alternative approach to direct heating with solar energy is to use the heated air from the collector as the cold-side thermal reservoir for a heat pump. In this configuration, the heat pump is then used for conventional space heating. Specialized phase-change storage techniques (e.g., wax impregnated wallboards) have also been developed in recent years, and these are particularly useful for solar houses. In some cases, entire housing complexes have been integrated with large, seasonal, energy storage facilities which provide hot air as required. For best performance, both passive and active methods may be combined in hybrid building heating systems.

### Solar Cooking

Solar cookers have been investigated for many decades, and some low cost commercial models are available. These cookers can be classified into three basic types. Hot-box designs consist of an insulated box with double glazing in which the cooking vessel is placed. Therefore the basic configuration is equivalent to that of a solar collector using the energy within the "collector" itself. Such cookers are oriented manually, and are limited to relatively low operating temperatures. The heat input and temperatures can be increased by incorporating reflectors within the box to increase the degree of concentration by a small amount.

Cookers that provide higher temperatures use concentrators (usually mirrors), and the vessel is mounted at the focal point. In this configuration, the vessel corresponds to the absorber in a concentrator-receiver collector. This type of design requires bright sunshine for successful operation, and care must be taken to minimize heat losses from the vessel at higher wind speeds. Folding-umbrella concentrators have been developed for such systems to enhance portability.

The hot-box and concentrator cookers cannot be used indoors and require a high level of solar insolation. Therefore their use is limited to rural and/or portable, camping applications where the cost of fuels may be excessive. To overcome these problems, the third approach is to use a collector-based system which transports energy with a suitable heat transfer fluid to an indoor "cooking range." High costs and other constraints, however, limit the use of such cookers at present.

### Industrial and Process Applications

Solar heat is extensively used for a number of industrial processes, such as distillation, salt/brine production,and drying of agricultural products. Over the years, considerable work has been done to develop other solar thermal systems, such as power plants, cooling/air-conditioning units, and detoxification/disinfection reactors. These are discussed further later on.

**Distillation.** Solar stills for producing drinking water from brackish or salt water have been used for more than a century. Though they may have various physical configurations (e.g., evaporation from wicks, flow over nonhorizontal surfaces), they are all thermally equivalent to the basin-type still (Fig. 7). In this design, solar energy is absorbed by water (either directly or via the dark lining of the basin) which evaporates and rises to the top of the enclosure. Because of the lower temperature of the cover, the vapor condenses, drains by gravity to the troughs on each side of the still, and is collected for future use.

Basin-type solar stills are either shallow with depths less than 0.02 m or deep with depths on the order of 0.1 m or

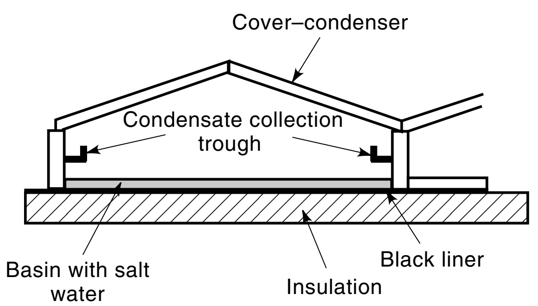


**Figure 7.** A schematic of a solar still.

more. Shallow designs are typically more expensive but produce more water even though they are operational only during the day. Deep stills continue to operate at night because of the thermal inertial of the larger body of water in the basin. From the viewpoint of heat transfer, a solar still is equivalent to a "no-flow" solar collector with an additional evaporation-condensation process within the still itself. Solar stills are typically characterized by their efficiency which is equivalent to the ratio of the useful heat transfer to the water to the solar radiation incident on the still surface.

**Salt/Brine Production.** Salt/brine production by solar heating and evaporation of sea or brackish water is also an industrial process used throughout the world. Typically, the salt, usually sodium chloride, is obtained in three stages in shallow ponds or pans. In the first step undertaken in the largest ponds, the solution is concentrated to a level at which it is fully saturated at about 23% salts. The concentrate is transferred to the second-stage pans, where calcium, magnesium, and iron sulfates and carbonates precipitate. Sodium chloride and magnesium and potassium chlorides and bromides are obtained in the final crystallizing ponds.

The heat transfer process in a solar evaporation process, whether for salt production or brine concentration, is similar to that in a solar still. However, no condensation is associated with this process, and in the absence of a cover, heat and mass transfer rates are significantly enhanced at high wind speeds. At the same time, rainfall reduces the production rate by diluting the concentrates in the ponds.

**Drying.** Drying of agricultural and forest products is another common use of solar thermal energy. Either a direct or an indirect approach may be used for this application. In direct systems, the product (e.g., grains, fruit) is spread out in a thin layer and exposed to solar radiation and wind. Mass is transferred from the grain surface by convective effects of the wind and the latent heat of evaporation is provided by solar radiation. Then moisture continues to diffuse outward from the interior because of the resulting concentration gradients, and drying occurs over a period of time.

Indirect systems have also been developed for drying wood, crops, etc. These are similar to conventional dryers, but part of the energy is provided by solar heat absorbed in a collector system. Another alternative is to use a greenhouse design in which the kiln itself is equivalent to a solar collector with internal circulation. In both cases, either a recirculation system or an open circuit configuration is possible.

**Power Generation.** Solar thermal power generation systems have been investigated for more than a hundred years. Early work was related to low-power ($<$100 kW) systems, mostly for irrigation. In recent decades, however, large systems generating up to 80 MWe (peak) have been operated experimentally. Typical systems have been based on concentrator-receiver collectors (e.g., parabolic troughs, heliostats) because heat engine efficiencies are a strong function of the temperature of the heat source. Alternatively, large solar ponds have been used to power low temperature power plants generating as much as 5 MWe.

Most solar thermal power plants have been based on the Rankine cycle, though Brayton and Stirling cycles have also been considered to increase the efficiency, particularly for high temperature systems. Depending on the power output and application, the overall configuration of the system can vary significantly. Typically, the solar energy collection system is a separate loop where the working fluid (organic/synthetic heat transfer medium) remains in the liquid phase throughout. Energy is transferred via a heat exchanger to a secondary medium (e.g., water/steam, fluorocarbons, organic fluids) which must satisfy the requirements of the power generation cycle. Energy storage units have also been incorporated in large power generation systems to provide better energy management.

**Cooling and Air Conditioning.** Solar heat has also been used in cooling applications. The most common approach is to use solar energy as the heat source for a conventional vapor absorption refrigeration system. Instead of using steam, hot water from solar collectors is used to supply energy to the generator in such systems. Continuously operating units for building cooling may require an auxiliary heat source to provide the necessary system performance. Simpler intermittent absorption systems can be used for food preservation. Prototype solar absorption cooling systems have been tested in various locations but have not yet reached the commercial stage.

Solar thermal energy has also been used in desiccant cooling systems which are based on a dehumidification-humidification process. Preconditioned air is dehumidified by a desiccant, an exothermic process which increases the temperature of the air. Then the air is cooled initially using exhaust (or other low temperature) air from the conditioned space, after which its temperature is brought down further by evaporative cooling. The desiccant itself is regenerated by solar heat. Exhaust air may also be used for this purpose if it is available at a suitable temperature. Though various types of solar desiccant cooling systems have been developed using both solid and liquid desiccants, these are mostly experimental at present.

**Detoxification/Disinfection.** Solar energy has been used for photocatalytic decomposition of hazardous wastes, such as PCBs and other organic compounds, and for killing bacteria and other pathogens. Systems are typically based on concentrator or flat-plate collectors, though shallow pond reactors have been used in some cases. Collectors are specially designed for this application because they must be highly transparent to ultraviolet radiation. This is essential because the oxidation-reduction reactions are driven only by UV radiation (wavelengths $\leq$388 nm based on the activation energy of titanium dioxide, the most commonly used catalyst), which comprises only about 4% to 6% of the total terrestrial solar radiation. The overall collector is otherwise relatively simple and requires no thermal insulation because the reaction rates are not a significant function of temperature.

## MODELING AND SIMULATION

Modeling of solar thermal processes is particularly important because of the high initial cost of many solar thermal systems. As a result, considerable work has been done to develop simulation tools for these systems. These include highly specialized models for individual or specific types of systems and more general transient or time-averaged models that can be used for a range of applications. Only the second group of models is discussed here because the others are not directly practical for most applications.

### Transient Models

A number of generalized transient models have been developed by different research groups around the world [e.g., Commission of European Communities (EMPG2/EURSOL), TRNSYS (United States), WATSUN (Canada)]. These are built on individual numerical simulation modules describing the transient performance of components that make up a typical (solar) thermal system. The modules are usually based on a 1-D approach because the uncertainties associated with typical solar thermal systems do not justify the increased computational cost of more complex 2-D or 3-D models. Limitations of current multidimensional computer models for complex thermal processes also make the 2-D and 3-D models impractical in most cases.

The generalized transient models are implemented in the form of large computer programs which include subroutines for the numerical solution of differential equations and utilities for mathematical analysis of various thermodynamic and transport processes. To simulate a given process/system, the modules describing the individual components are linked together in series and/or parallel as required. Then the system performance is studied by numerically integrating the set of time-dependent differential equations with a given set of parameters and initial conditions. The results are output in various forms, and with some programs, it is possible to conduct an economic analysis of a given system/process using the results of the simulation.

The performance of solar thermal systems is a strong function of local climatic conditions. Thus, some programs generate a synthetic climate that is used as part of the simulation process. Various transient forcing functions are also included in the simulation packages for the same purpose. Meteorological data, averaged over suitable periods of time (e.g., weeks, month, years, depending on the application), are used directly in many cases.

### Time-Averaged Models

Transient models are not typically used for evaluating small-scale, residential type solar thermal systems because of time and cost constraints. Instead, time-averaged methods that are used to obtain quick results have been developed for such applications (11). If the temperature of the fluid at the inlet of the collector is known a priori, one approach is to evaluate the useful energy based on available weather data and an estimate of the system losses (which must be less than the absorbed radiation if there is to be any useful energy). For a given system design, these are typically quantified by a parameter known as the utilizability, which is the useable fraction of the total incident energy available over any given period (hour, day, etc.).

Utilizability methods are usually based on the monthly averaged values and are widely used, particularly for swimming pool heating, passive and hybrid heating, and air heating systems. For many liquid collectors, however, there may be large intramonth variations in the critical radiation level (i.e., the radiation level at which the incident radiation exactly equals the absorber losses, and the utilizability is zero). As a result these methods are not applicable for such systems.

An alternative approach is to correlate the results of a large number of simulations and use the correlation to predict the performance of similar systems. This is the basis of the $f$-chart method which is used to estimate the fraction $f$ of the total energy required for a specific application that can be supplied by solar radiation. This parameter is usually obtained as a function of the heat loss ($X$) from the collector and the energy ($Y$) absorbed by the collector, both of which are normalized with respect to the heating load. Separate correlations for $f$ are available for air- and water-based systems, and correction factors which account for energy storage have been developed. Because the functions are obtained using a curve fit, the $f$-chart method can be used only for the specified range of parameters and where the minimum load temperatures are about 20°C. More advanced methods combining the utilizability and $f$-chart concepts have also been developed to overcome this minimum temperature limitation but are not commonly used.

The utilizability, $f$-chart, and related methods are directly applicable to active collector-based systems. In contrast, the heat transfer process in passive "solar buildings" is related closely to its architectural design. Nevertheless, models based on the utilizability concept and correlation-based methods have been developed for such applications. Specialized charts and methods based on past experience with passive heating are also used in system design. These may be strictly empirical or may be based on more complete analysis of the building heat transfer process. Similar detailed analyses may also be required for large active systems where the simple utilizability and $f$-chart methods are not adequate.

## RESOURCES

Numerous books covering theoretical and practical aspects of solar energy and its utilization have been published during the past 25 years. Probably the most complete single volume on solar thermal systems is by Duffie and Beckman (12). A more exhaustive 10 volume compilation of work on solar heating technologies has also been published recently by MIT Press (13). Most handbooks on energy systems engineering provide some coverage of solar heating, but the most useful one, limited to solar energy systems, is by Kreider and Kreith (14).

The primary professional organization associated with solar heating is the International Solar Energy Society that has affiliated national organizations worldwide. Publications of these organizations provide an useful perspective on progress in solar energy. The results of the latest research on solar thermal systems are published in a number of periodicals related to heat transfer and thermal engineering and in a number of specialized journals related to solar and alternative energy.

Solar radiation data are available from various sources, particularly the national meteorological offices of individual countries [e.g., National Weather Service (NWS), National Oceanic and Atmospheric Administration (NOAA), and National Climatic Data Center in the US]. Extensive compilations of data obtained from sources worldwide can also be obtained from the World Radiation Data Center in St. Petersburg, Russia.

Finally, it is also important to note that a significant fraction of research on solar thermal systems has been funded by government agencies throughout the world. Reports published through the relevant organizations (e.g., DoE, NASA, NREL in the US) are extremely important sources of detailed information on many of the original research projects. Technical standards have also been developed by professional organizations (e.g., ASHRAE, SRCC, and FSEC in the US) for components and systems related to active water and space heating. Industry associations (e.g., SEIA in the US) are also an important source of information regarding commercial aspects of solar energy.

## BIBLIOGRAPHY


1. W. C. Dickinson and P. N. Cheremisinoff (eds.), *Solar Energy Technology Handbook. Part A. Engineering Fundamentals,* New York: Dekker, 1980, p. 12.
2. J. Lean, The Sun's variable radiation and its relevance for Earth, *Ann. Rev. Astron. Astrophys.,* **35**: 33–67, 1997.
3. M. Iqbal, *An Introduction to Solar Radiation,* New York: Academic Press, 1983.
4. M. Noia, C. F. Ratto, and R. Festa, Solar irradiance estimation from geostationary satellite data: 1. Statistical models, and 2. Physical models, *Solar Energy,* **51**: 449–465, 1993.
5. C. Gueymard, P. Jindra, and V. Estrada-Cajigal, A critical look at recent interpretations of the Angstrom approach and its future in global solar radiation predictions, *Solar Energy,* **54**: 357–363, 1995.
6. C. Hottel, A simple model for estimating the transmittance of direct solar radiation through clear atmospheres, *Solar Energy,* **18**: 128, 1976.
7. J. Davies and D. C. McKay, Evaluation of selected models for estimating solar radiation on horizontal surfaces, *Solar Energy,* **43**: 153–168, 1989.
8. D. T. Reindl, W. A. Beckman, and J. A. Duffie, Evaluation of hourly tilted surface radiation models, *Solar Energy,* **45**: 9–17, 1990.
9. W. T. Welford and R. Winston, *The Optics of Nonimaging Concentrators,* New York: Academic Press, 1978.
10. G. Beckmann and P. V. Gilli, *Thermal Energy Storage,* Vienna, Austria: Springer-Verlag, 1984.
11. T. A. Reddy, *The Design and Sizing of Active Solar Thermal Systems,* Oxford, UK: Clarendon Press, 1987.
12. J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes,* 2nd ed., New York: Wiley, 1991.
13. C. A. Bankston (ed.), *Solar Heat Technologies: Fundamentals and Applications.* Vol. 1–10 (with individual volume titles and editors), Cambridge, MA: MIT Press, 1993.
14. F. Kreider and F. Kreith, *Solar Energy Handbook,* New York: McGraw-Hill, 1981.


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**SOLAR HEATING STORAGE.** See THERMAL ENERGY STORAGE.

**SOLENOIDS.** See SUPERCONDUCTING ELECTROMAGNETS.

**SOLID ELECTROLYTES.** See ELECTROLYTES.