2 The Solar Energy Option: An Overview of Thermal Applications

In Chapter 1, the solar energy option has been identified as one of the promising alternative energy sources for the future. The nature of this source, its magnitude and its characteristics have been described, and a classification of the various methods-direct and indirect-for utilising solar energy has been given. In this chapter, attention will be focussed on the direct thermal approach. Various devices used for thermal collection and storage will be described in brief. This will be followed by an overview of a number of solar thermal applications in many of which these devices are used.

Other methods for utilising solar energy through photovoltaic conversion, wind energy, etc., will be described in Chapter 9.

2.1 DEVICES FOR THERMAL COLLECTION AND STORAGE

In any collection device, the principle usually followed is to expose a dark surface to solar radiation so that the radiation is absorbed. A part of the absorbed radiation is then transferred to a fluid like air or water. When no optical concentration is done, the device in which the collection is achieved is called a *flat-plate collector* (FPC). The flat-plate collector is the most important type of solar collector because it is simple in design, has no moving parts and requires little maintenance. It can be used for a variety of applications in which temperatures ranging from 40°C to about 100°C are required.

A sketch of a liquid flat-plate collector is shown in Fig. 2.1. As stated earlier, it consists of an absorber plate on which the solar radiation falls after coming through a transparent cover (usually made of glass). The absorbed radiation is partly transferred to a liquid flowing through tubes which are fixed to the absorber plate or are integral with it. This energy transfer is the useful gain. The remaining part of the radiation absorbed in the absorber plate is lost by convection and re-radiation to the surroundings from the top surface, and by conduction through the back and the edges. The transparent cover helps in reducing the losses by convection and re-radiation, while thermal insulation on the back and the edges helps in reducing the conduction heat loss. The liquid most commonly used is water. A liquid flat-plate collector is usually held tilted in a fixed position on a supporting structure, facing south if located in the northern hemisphere. It is discussed in detail in Chapter 4.

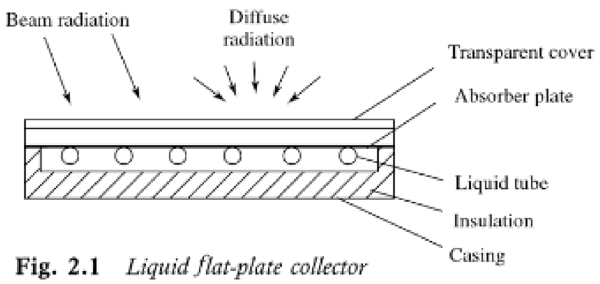

Fig. 2.1 *Liquid flat-plate collector*

In order to reduce the heat lost by re-radiation from the top of the absorber plate of a flat-plate collector, it is usual to put a selective coating on the plate. The selective coating exhibits the characteristic of a high value of absorptivity for incoming solar radiation and a low value of emissivity for out-going re-radiation. As a result, the collection efficiency of the flat-plate collector is improved. Further improvement in the collection efficiency (or in the operating temperature) is obtained by evacuating the space above the absorber plate and leads to the design of an evacuated tube collector.

An *evacuated tube collector* (ETC) consists of a number of cylindrical modules mounted side-by-side on a common frame. Figure 2.2 shows a schematic diagram of one type of evacuated tube module. It consists of two concentric glass tubes, with the annular space between them being evacuated. The outer surface of the inner glass tube is selectively coated. The incoming solar radiation is absorbed on this surface and partly conducted inwards through the tube wall. The inner tube is filled with water, and the heat is transferred to the water by thermosyphon circulation. It is to be noted that the heat loss by convection to the surroundings is reduced significantly due to the vacuum in the annular space. This results in an improvement in the collection efficiency. The evacuated tube collector is discussed further in Chapter 4.

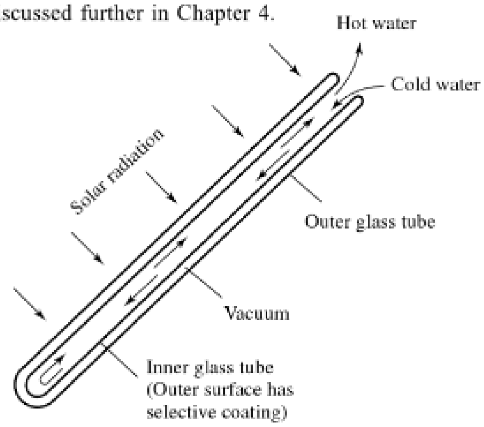

Fig. 2.2 *Schematic diagram of an evacuated tube collector module*

A schematic cross-section of a conventional flat-plate collector for heating air (commonly referred to as a *solar air heater)* is shown in Fig. 2.3. The construction of such a collector is essentially similar to that of a liquid flat-plate collector except for the passages through which the air flows. These passages have to be made larger in order to keep the pressure drop across the collector within manageable limits. In the diagram shown, the air passage is simply a parallel plate duct. The solar air heater is discussed further in Chapter 5.

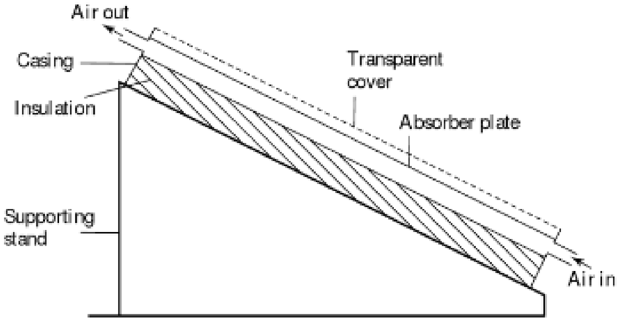

Fig. 2.3 *Solar air heater*

When higher temperatures are required, it becomes necessary to concentrate the radiation. This is achieved using *focussing* or *concentrating collectors.* A schematic diagram of a typical line-focussing concentrating collector is shown in Fig. 2.4. The collector consists of a concentrator and a receiver. The concentrator shown is a mirror reflector having the shape of a cylindrical parabola. It focusses the sunlight on to its axis, where it is absorbed on the surface of the absorber tube and transferred to the fluid flowing through it. A concentric glass cover around the absorber tube helps in reducing the convective and radiative losses to the surroundings. In order that the sun's rays should always be focussed on to the absorber tube, the concentrator has to be rotated. This movement is called *tracking.* In the case of cylindrical parabolic concentrators, rotation about a

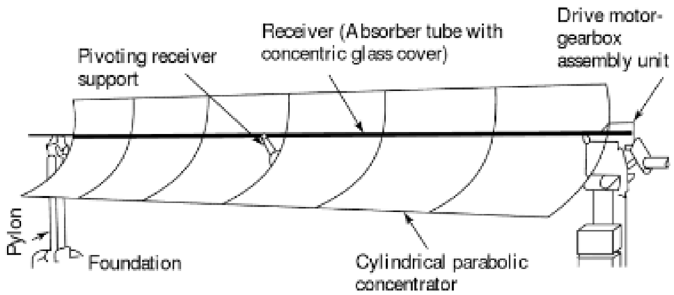

Fig. 2.4 *Cylindrical parabolic concentrating collector*

single axis is generally required. Fluid temperatures up to 400°C can be achieved in cylindrical parabolic focussing collector systems. The generation of still higher working temperatures is possible by using paraboloid reflectors (Fig. 2.5) which have a point focus. These require two-axis tracking so that the sun is in line with the focus and the vertex of the paraboloid. Concentrating collectors are described in Chapter 6.

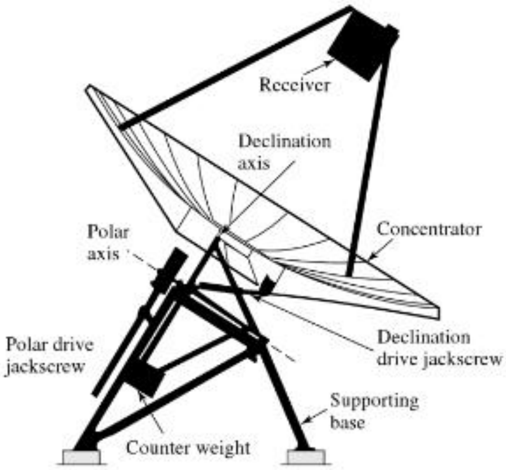

Fig. 2.5 *Paraboloid concentrating collector*

Typical values of efficiency obtained from flat-plate collectors, evacuated tube collectors, line-focussing collectors and paraboloid dish collectors are shown in Fig. 2.6. The efficiency is plotted as a function of the operating temperature and as is to be expected, it decreases with increasing temperature. The data presented in Fig. 2.6 is useful for doing approximate calculations of thermal systems using solar collectors. Such calculations help in giving estimates of the collector area required for a given performance. Alternatively they can be used for obtaining a rough idea of the performance of a solar thermal system using a certain number of collectors of a specified type.

As stated earlier, one of the major problems associated with the utilisation of solar energy is its variability. For this reason, most applications require some type of *energy storage* system. The purpose of such a system is to store energy when it is in excess of the requirement of an application and to make it available for extraction when the supply of solar energy is absent or inadequate. Energy storage can be in various forms – thermal, electrical, mechanical or chemical. Thermal energy can be stored as sensible heat or as latent heat. Sensible heat storage is usually done in an insulated container containing a liquid like water or a porous solid in the form of pebbles or rocks (Fig. 2.7). The first type is preferred with liquid collectors, while the second type is compatible with air heaters.

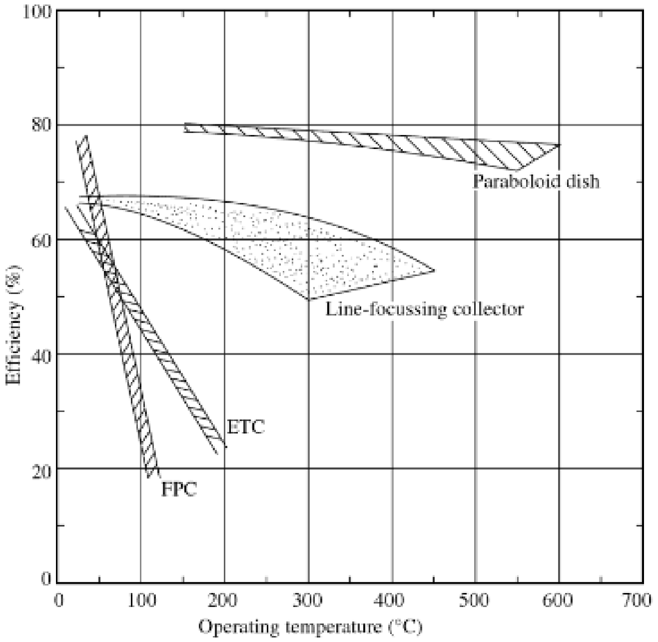

Fig. 2.6 *Efficiency of various types of collectors as a function of operating temperature (Adapted from Gehlisch et al. [1] and Rabl [2])*

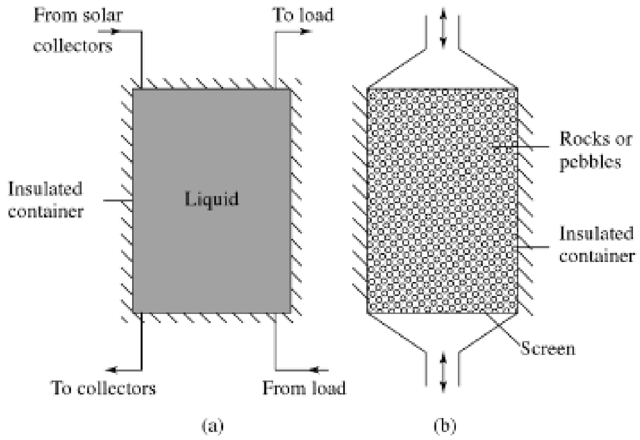

Fig. 2.7 *Schematics of two forms of sensible heat storage: (a) liquid, (b) porous solid*

In the case of latent heat storage, heat is stored in a substance when it melts and extracted when the substance freezes. Sensible heat storage systems operate over a range of temperatures, while latent heat storage systems operate essentially at the temperature at which the phase change takes place. Both these forms of thermal storage are analysed in Chapter 7.

Apart from thermal storage, other forms of storage are possible if the application involves some energy conversion process. For example, if mechanical work is being obtained after conversion, storage could be done in large sized flywheels or in compressed air. It has been suggested that compressed air could be stored in large underground chambers. Similarly, if electrical power is being obtained after conversion, storage could be in the form of electric batteries. Many types of electric batteries are used for the purpose, the most common being lead-acid batteries.

A novel device which combines the functions of both collection and storage is the *solar pond.* It consists of an expanse of water about a metre or two in depth in which salts like sodium or magnesium chloride are dissolved. The concentration of the salt is more at the bottom and less at the top. Because of this, the bottom layers of water are denser than the surface layers even if they are hotter and natural convection does not occur. Thus, the heat from the sun's rays absorbed at the bottom of the pond is retained in the lower depths, and the upper layers of water act like a thermal insulation. The solar pond is taken up for detailed consideration in Chapter 8.

2.2 THERMAL APPLICATIONS

We will now survey a number of thermal applications. These are

1. water heating
2. space heating
3. space cooling and refrigeration
4. power generation
5. distillation
6. drying, and
7. cooking.

For each application, a variety of systems in use are described and specifications and costs of typical systems available in India are given. A few numerical examples are also solved to show how systems can be approximately sized or alternatively how the performance of installed systems can be estimated.

It may be noted that most of the above applications use one or more of the devices described in Sec. 2.1. It may also be noted that applications 1, 2, 5, 6 and 7 use the heat energy collected from solar radiation directly, while applications 3 and 4 use the collected heat in thermodynamic cycles to obtain cooling in one case and work in the other. From an economic stand-point, applications which use the collected heat directly are obviously more attractive.

2.2.1 Water Heating

We begin with descriptions of water-heating systems because solar water heating is one of the most attractive solar thermal applications from an economic standpoint. In many countries of the world, it is already competing on equal terms with systems using other energy sources. In India, a large number of systems have been installed. Most of the systems use flat-plate collectors. It is cumulatively estimated that the total area of the flat-plate collectors in the systems installed in India till June 2006 is about 1.5×10^6 m^2. The hot water is used for domestic purposes or for meeting the needs of industries and commercial establishments.

Solar water-heating systems can be classified into two categories:

1. natural circulation (thermosyphon) systems and
2. forced circulation systems.

Natural Circulation Systems A simple, small-capacity natural circulation system, suitable for domestic purposes, is shown in Fig. 2.8 and in Plate 2.1. The two main components of the system are the liquid flat-plate collector and the storage tank, the tank being located above the level of the collector. As water in the collector is heated by solar energy, it flows automatically to the top of the water tank and it is replaced by cold water from the bottom of the tank. Hot water for use is withdrawn from the top of the tank. Whenever this is done, cold water automatically enters at the bottom. An auxiliary-heating system is sometimes provided for use on cloudy or rainy days.

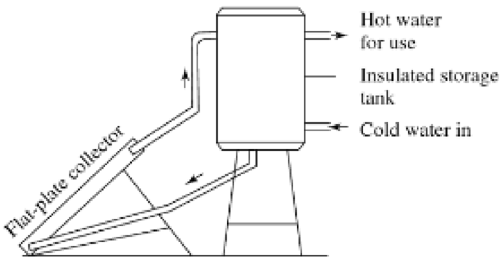

Fig. 2.8 *Small capacity natural circulation water heating system*

Solar water heating is a good example to illustrate one of the assets of the direct use of solar energy which has not been mentioned so far. This is the possibility of matching the temperature achieved in the heating device (in this case the flat-plate collector) with the temperature required for end use. As a result of this matching, the thermodynamic efficiency based on considerations of availability of energy can be shown to be higher in the case of a solar water heating system than a water heating system using natural gas or electricity.

Solar water heaters of the natural circulation (thermosyphon) type were used fairly widely in many countries from the beginning of the 20th century till about 1940 until cheap oil and natural gas became available. Now they are being installed again in large numbers.

In India, the market for domestic solar water heating systems has been growing steadily. Most of the systems have capacities in the range of 100 to 200 litres per day, use one or two flat-plate collectors having a face area of about 2 m^2 each, and deliver hot water in the temperature range of 50 to 70°C. The installed cost in 2006 was about Rs 180 per litre/day capacity.

The specifications of a typical 125 litre capacity thermosyphon system are given below:

Flat-plate collector

Gross area	: 2.23 m^2
Cover	: Toughened glass, single, 4 mm thick
Absorber plate	: Copper sheet (0.20 mm thick) with selective coating
Risers for water flow	: Copper tubes (12 mm O.D.); 9 numbers
Casing	: Extruded aluminium section with aluminium sheet on back side
Side insulation	: 25 mm thick glass wool
Bottom insulation	: 50 mm thick glass wool

Storage tank

Shape	: Cylindrical shell (with axis horizontal) made from SS 304 (1.2 mm thick)
Capacity	: 125 litres
Insulation	: 100 mm thick glass wool on all sides

Example 2.1 *Estimate the temperature rise of the water in a 100-litre capacity thermosyphon solar water-heating system during a typical day of operation. Estimate also the electricity saved because of the use of a solar water heater and the corresponding reduction in the monthly electricity bill.*

Solution We will perform an approximate calculation based on the following assumptions:

1. The system has one flat-plate collector with an absorber plate area of 2 m^2.
2. The solar radiation falling on the collector during a typical day is 5 kWh/ m^2. (This is a good assumption for many locations in India for 250 to 300 days in a year.)
3. The collector efficiency is 50 per cent. From Fig. 2.6, this corresponds to an operating temperature of 70°C.
4. No water is withdrawn for use during the day.

Equating the energy absorbed in the collector during the day to the enthalpy change of the water, we have

Solar radiation incident on the collector per unit area per day × Collector area × Collector efficiency = Mass of water to be heated per day × Specific heat of water × Temperature rise of water

$$(5 \times 3600) \times 2 \times 0.50 = 100 \times 4.2 \times \Delta T$$

where ΔT = temperature rise of water.

Thus ΔT = 43°C.

Assuming that the water temperature in the morning was 20°C, the temperature around 4 or 5 p.m. will be 63°C. Thus the value assumed for the efficiency of the collector is justified.

In order to calculate the electrical energy saved, we assume that an electric geyser has an efficiency of 95 per cent. Thus, electricity saved every day

$$= \frac{5 \times 2 \times 0.50}{0.95} = 5.26 \text{ kWh}$$

Taking the cost of electricity to be Rs 3.50 per unit, money saved per day

$$= \text{Rs } 5.26 \times 3.50 = \text{Rs } 18.42$$

Reduction in monthly electricity bill

$$= \text{Rs } 18.42 \times 30 = \text{Rs } 553$$

This is a significant reduction.

A domestic water heating system based on evacuated tube collectors is shown in Plate 2.2. The system consists of a number of evacuated tube modules connected directly to a storage tank. The inside of each evacuated tube module is filled with water, which gets heated up and a thermosyphon circulation is established. Hot water flows out of each module and cold water from the storage tank takes its place. Such domestic water heating systems are becoming popular in India. A commercially available system has 15 modules with a storage tank of 100 litres capacity. Each module made of borosilicate glass is 1.5 m long and the diameters of the outer and inner tubes are 47 and 37 mm, respectively. The cost of such a system presently is about Rs 18 000.

Forced Circulation Systems When a large amount of hot water is required for supplying process heat in an industry or in a commercial establishment, a natural circulation system is not suitable. Large arrays of flat-plate collectors are then used and forced circulation is maintained with a water pump (Plate 2.3). The restriction that the storage tank should be at a higher level is thus removed. A schematic diagram of a typical closed loop system is shown in Fig. 2.9. Water from a storage tank is pumped through a collector array, where it is heated and then flows back into the storage tank. Whenever hot water is withdrawn for use, cold make-up water takes its place because of the ball-float control shown. The pump for maintaining the forced circulation is operated by an on-off controller which senses the difference between the temperature of the water at the exit of the collectors and a suitable location inside the storage tank. The pump is switched on whenever this difference exceeds a certain value and off when it falls below a certain value. Provision is also usually made for an auxiliary heater. In Fig. 2.9, the auxiliary heater is shown as an immersion heater located in the storage tank. Often it is located on the hot water line leading out of the storage tank. Solar water systems of the type shown in Fig. 2.9 are well suited for factories, hospitals, hotels, offices, etc. Typically these systems cost about Rs 140 per litre/day of hot water.

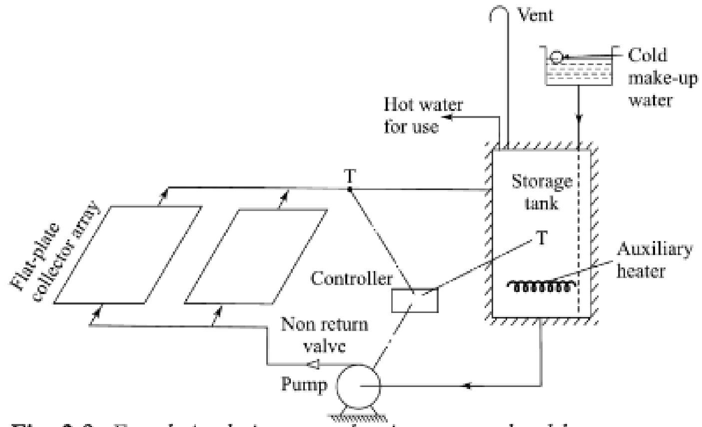

Fig. 2.9 *Forced circulation water heating system-closed loop configuration*

Many variations are possible in the configuration shown in Fig. 2.9. A popular variation is one with an open loop configuration shown in Fig. 2.10. In such a configuration, the water flows from a cold water tank through the collectors to an insulated hot water storage tank from where it is withdrawn for use. The control of such a system is usually designed so that hot water at the required temperature flows out of the collector array, the flow rate being adjusted to meet this temperature requirement. The specifications of a large open-loop system installed at a textile mill in Mumbai in 1991 are as follows:

System capacity	: 100 000 litres of hot water per day
Average temperature of inlet feed water	: 25°C
Required outlet temperature	: 80°C
Number of flat-plate collectors (each about 2 m^2 in area)	: 1021
Capacity of cold water tanks	: 100 000 litres
Capacity of hot water tanks	: 175 000 litres

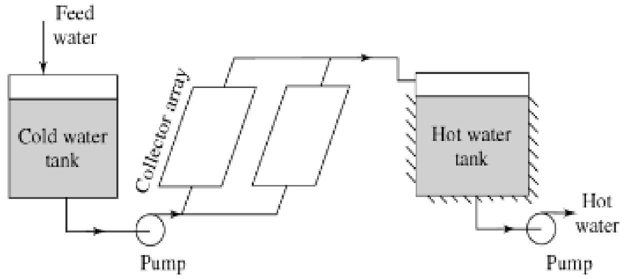

Fig. 2.10 *Forced circulation water heating system-open loop configuration*

It is claimed that this system meets the design specification for 300 days in the year and helps to save about 200 000 litres of oil annually.

Figure 2.11 shows a schematic diagram of one more forced circulation system for supplying process heat. In this case, a concentrating collector array is used to heat pressurized water or a thermic fluid to a temperature above 100°C and the heated liquid is kept in a storage tank. A heat exchanger is used to extract energy from the heated liquid and obtain either hot water or low pressure steam for industrial or commercial use. An auxiliary heater is provided in the line in order to supply make-up energy in case the solar energy is inadequate.

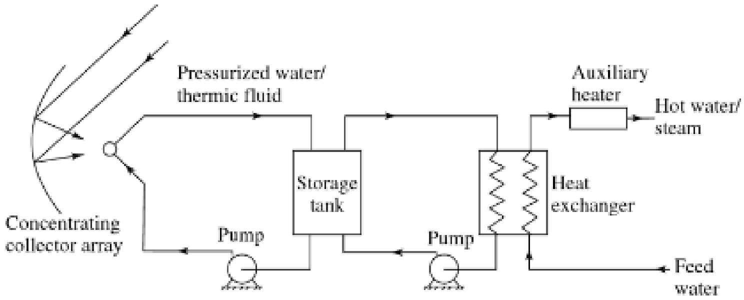

Fig. 2.11 *Solar industrial process heating system using a concentrating collector array*

An industrial process heat system of this type has been installed in 2006 at a dairy in Latur, Maharashtra to provide hot water at 95°C. This water is used for pasteurisation of 20 000 to 25 000 litres of milk per day. The solar system is an add-on to an existing boiler, which is run with furnace oil [3]. The boiler has now been kept as a stand-by unit. The specifications of the solar system are as follows:

Collector array[+]	: One paraboloid dish with an aperture area of 160 m^2
Working fluid in collector	: Pressurized water at 20 bar
Temperature of water leaving collector	: 160–180°C
Storage tank capacity	: 5000 litres
Heat transfer rate in heat exchanger	: 4.18×10^5 kJ/h
Temperature of hot water supplied for pasteurisation	: 95°C

2.2.2 Space Heating

We now turn our attention to space-heating systems. Space heating is of particular relevance in colder countries where a significant amount of energy is required for this purpose. In India, it is of importance mainly in the northern and north-eastern regions in winter.

+ More details of the paraboloid concentrating collector are given in Sec. 6.5.

Active Methods We will first describe space-heating systems using active methods. An active method is one which utilizes a pump or a blower to circulate the fluids involved in the space-heating system. One system is illustrated in Fig. 2.12. In this system, water is heated in solar flat-plate collectors (A) and stored in the tank (B). Energy is transferred to the air circulating in the space to be heated by means of the water-to-air heat exchanger (E). Two pumps (C) provide forced circulation between the collectors and the tank, and between the tank and the heat exchanger. Provision is also made for adding auxiliary heat (D). Since the solar energy is first being used to heat water, the system shown in Fig. 2.12 can be easily modified to be a two-in-one system supplying hot water as well as hot air for space heating.

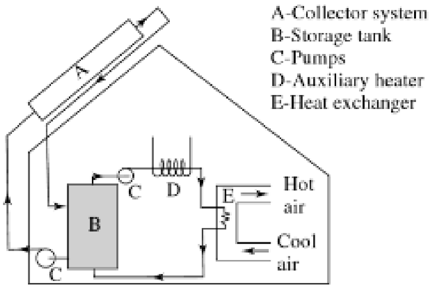

Fig. 2.12 *Schematic diagram of a space heating system using liquid flat-plate collectors*

An alternative approach to space heating is to heat air directly in solar air heaters (A), as shown in Fig. 2.13. The heat is then stored in a porous bed storage (B) packed with rock, gravel or pebbles. Energy is extracted and transferred to the space to be heated by blowing cool air through the porous bed. Once again an auxiliary heater (D) is provided for supplying make-up heat.

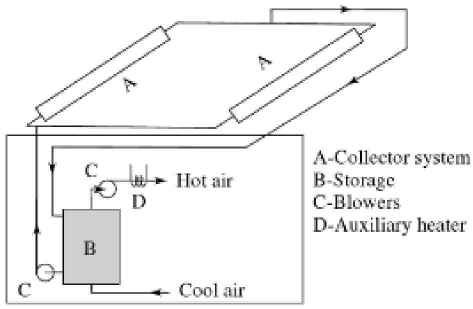

Fig. 2.13 *Schematic diagram of a space heating system using solar air heaters*

Another type of space heating system which is being adopted in cold countries consists of an unglazed transpired collector (UTC) (A), fixed in front of a sun-facing

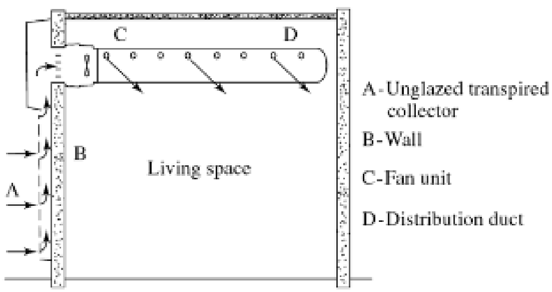

Fig. 2.14 *Schematic diagram of a UTC-based space heating system*

wall (*B*), a fan unit (*C*) and an air-distributing duct (*D*) (Fig. 2.14). A UTC (details are given in Chapter 5) is usually a perforated dark-coloured metallic plate and gets heated up by the absorption of solar radiation. Ambient air, drawn through the holes of the UTC by the fan, gets heated as it flows in the space between the UTC and the wall, and is subsequently distributed through the duct to the living space. Over 70 such systems, with collector areas between 500 and 10 000 m^2 have been installed in Canada, USA, Germany and Japan [4].

Passive Methods In contrast to the active methods, space heating giving a fair degree of comfort can also be done by adopting passive methods. A passive method is one in which thermal energy flows through a living space by natural means without the help of a mechanical device like a pump or a blower.

A schematic diagram of a passive space-heating system designed by Professor Trombe is shown in Fig. 2.15. The south face+ of the house to be heated is provided with a single or double glazing. Behind it is a thick, "black", concrete wall, which absorbs the sun's radiation and serves as a thermal storage. Vents (*A* and *B*), which can be kept open or closed, are provided near the top and bottom of the storage wall. The whole unit consisting of the storage wall with vents and the glazing is referred to as a *Trombe wall.*

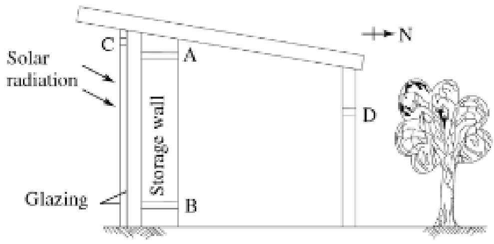

Fig. 2.15 *Space heating by passive methods-the Trombe wall*

During the day, both vents A and B are kept open. The air between the inner glazing and the wall gets heated and flows into the living space through the top vent. Simultaneously, the cooler air from the room is pulled out of the living space through the bottom vent. Thus, a natural circulation path is set up. Some energy transfer to the living space also takes place by convection and radiation from the inner surface of the storage wall. During the night, both vents are closed and energy transfer takes place only by convection and radiation from the inner surface.

The Trombe wall design can also provide summer ventilation by using vents *C* and *D* near the top of the glazing and on the north-facing wall. On a hot summer day, vents *B, C* and *D* would be kept open, while vent *A* would be kept closed. The heated air between the glazing and the wall would then flow out through vent *C,* drawing air from the living space to replace it. This in turn would cause air to be pulled in from outside through vent D. Vent *D* should be located such that the air pulled in through it comes from a shaded and cool area. The presence of an

+ The south face is for locations in the northern hemisphere. The north face would be used in the southern hemisphere.

overhang on the roof of the house should also be noted. This prevents direct radiation from falling on the glazing during summer and makes the ventilation more effective.

Another passive design approach for space heating is to construct a sunspace or greenhouse next to the living space to be heated. The sunspace is located on the south side of the building. It has a large glass roof and there is a thick wall with vents at the top and bottom linking it with the living space (Fig. 2.16). Thus the sunspace acts as a buffer zone between the living space and the outdoor conditions. During the day, the sunspace gets heated up and warm air enters the living space through the top opening *A*. Cooler air from the living space is pulled out through the bottom opening *B* thereby establishing a natural circulation flow. In addition, energy is stored in the link wall. During the night, the openings are closed and the energy stored in the link wall is conducted through it and transferred to the living space by convection and radiation from the inner surface.

Many variations are possible in the design described.

1. In order to increase the energy storage capacity in the sunspace room, concrete benches, water drums or rock beds on the floor can be provided.
2. In order to increase the solar radiation entering the sunspace, the side walls may also be provided with glazing.

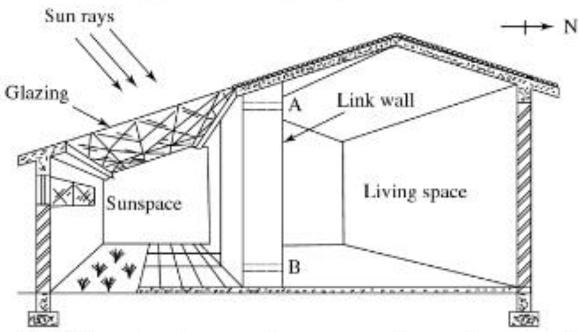

Fig. 2.16 *Schematic diagram of a sunspace for passive space heating*

3. Since the area of the glass in the sunspace is large, the thermal loss during the night can be excessive. This can be reduced by providing a moveable cover on the glass during the night. The moveable cover can also be used for shading the glazing in summer during the day to prevent overheating.

Generally, a building may incorporate more than one passive heating feature. Figure 2.17 shows the plan of one such building at Choglamsar, Leh [5]. The building has an attached greenhouse and also Trombe walls. The floor of the greenhouse consists of solid masonry to provide thermal storage and it is fitted with a moveable internal shade. The performance of the building was monitored. It was seen that in the month of December when the maximum and minimum ambient temperatures at Choglamsar were 2.8°, and –9.4°C respectively, the corresponding temperatures of room 5 were 21.6° and 6.8°C; and in the hall were 17.0° and 4.6°C respectively. Thus because of the passive heating features, the temperatures inside were about 14° to 18°C higher than the temperatures outside.

The use of passive techniques for heating, as well as ventilation and cooling is not new. They were adopted by almost all the ancient civilisations. Excavations at Mohenjodaro and Harappa have shown that the buildings had thick mud brick walls with no openings on the north side so as to keep away the winter winds. Also many of the building designs were of the courtyard type, which is a good layout for regions having climatic extremes and large temperature variations during the day.

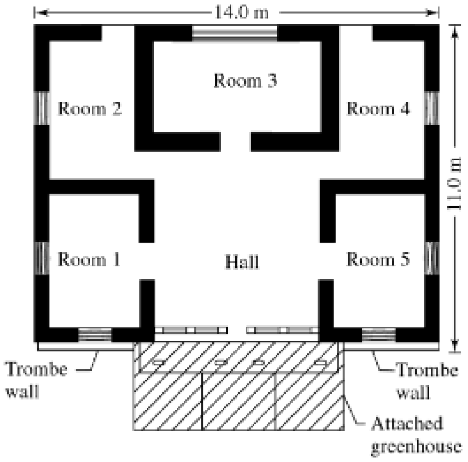

Fig. 2.17 *Plan of S.O.S. dormitory building, Choglamsar, Leh [5]*

The question which may well be asked is why passive methods are not used more extensively. The answer lies in the fact that while a passive method does provide comfort, it does not provide the same degree of comfort as an active heating system. For example, a passive method might result in a daily temperature fluctuation of 10°C in a living space and might not be able to take care of an extreme climatic condition adequately. On the other hand, a properly designed active method would probably result in a smaller variation of 3° or 4°C, and would take care of all situations. For this reason, with increased expectations of comfort, passive methods have been discarded. Now, however, with rising fossil fuel costs, people are again realising the virtues of passive methods and they are being slowly "rediscovered". In many new buildings, hybrid systems using both passive and active methods are being considered. In this way, the size of the active system is considerably reduced.

2.2.3 Space Cooling and Refrigeration

One of the interesting thermal applications of solar energy is for the purpose of cooling. Space cooling may be done with the objective of providing comfortable living conditions (air-conditioning) or of keeping a food product cold (refrigeration). Since the energy of the sun is being received as heat, the obvious choice is a system working on the absorption refrigeration cycle which requires most of its energy input as heat. Cooling is required most in summer. Hence, in this case, there is a seasonal matching between the energy needs of the space cooling system and the availability of solar radiation.

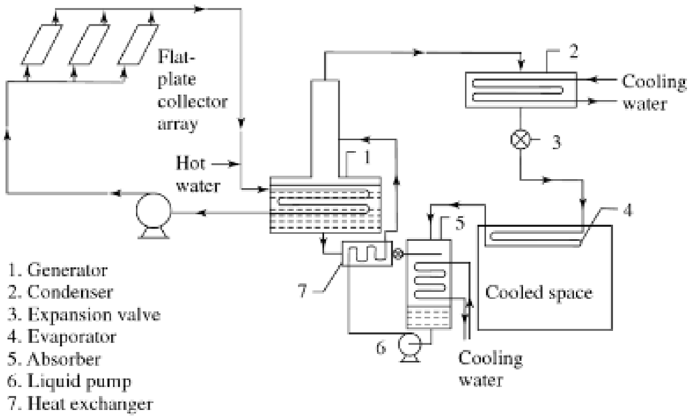

Fig. 2.18 *Solar absorption refrigeration system*

A diagram of a simple solar operated absorption system is shown in Fig. 2.18. Water heated in a flat-plate collector array is passed through a heat exchanger called the generator, where it transfers heat to a solution mixture of the absorbent and refrigerant, which is rich in the refrigerant. Refrigerant vapour is boiled off at a high pressure and goes to the condenser where it is condensed into a high pressure liquid. The high pressure liquid is throttled to a low pressure and temperature in an expansion valve, and passes through the evaporator coil. Here, the refrigerant vapour absorbs heat and cooling is therefore obtained in the space surrounding this coil. The refrigerant vapour is now absorbed into a solution mixture withdrawn from the generator, which is weak in refrigerant concentration. This yields a rich solution which is pumped back to the generator, thereby completing the cycle. The rich solution flowing from the absorber to the generator is usually heated in a heat exchanger by the weak solution withdrawn from the generator. This helps to improve the performance of the cycle. Some of the common refrigerant-absorbent combinations used are ammonia-water and water-lithium bromide, the latter being used essentially for air-conditioning purposes. Typical values for the coefficient of performance (the ratio of the refrigerating effect to the heat supplied in the generator) range between 0.5 and 0.8.

Unfortunately, the installation cost of a solar absorption refrigeration system is high because of the cost of the large collector array required. Thus commercialisation has not taken place although a few demonstration units have been set up. As an example, the specifications and cost of a solar air-conditioning plant installed recently near Ahmedabad are given below [6]:

Cooling cycle	: Water-lithium bromide absorption cycle
Capacity	: 25 tonnes of refrigeration
Solar collectors	: Heat pipe evacuated tube collectors
Collector area	: 280 m^2
Heat storage tank	: 5000 litres
Area covered for cooling	: 227 m^2
Indoor air temperature	: 18-19°C
Hours of operation per day	: 9
Cost of plant	: Rs 58 lakh (Solar unit Rs 40 lakh. Air-conditioning unit Rs 18 lakh)

2.2.4 Power Generation

The generation of electrical power is one of the most important applications of an energy source. Here we shall discuss only methods for solar thermal power generation.* Other methods using solar energy for generating electrical power (either directly or indirectly) will be described in Chapter 9.

Solar thermal power cycles can be classified as low, medium and high temperature cycles. Low temperature cycles work at maximum temperatures of about 100°C, medium temperature cycles work at maximum temperatures up to 400°C, while high temperature cycles work at temperatures above 400°C.

Low temperature systems use flat-plate collectors or solar ponds for collecting solar energy. Systems working on the solar chimney concept have also been suggested. Medium temperature systems use the line-focussing parabolic collector technology. High temperature systems use either paraboloid dish collectors or central receivers located at the top of towers.

Low Temperature Systems A diagram of a typical low temperature system using flat-plate collectors and working on a Rankine cycle is shown in Fig. 2.19.

---

* From a historical viewpoint, it is of interest to note that the first experiments on the generation of solar thermal power in India were conducted by an Englishman, William Adams, about one hundred years ago. Adams stayed in Colaba, Mumbai and performed his experiments in the compound of his bungalow. He used a spherical reflector 12 m in diameter, made from sheets of glass mirror. The sun's rays were focussed on a boiler having a capacity of about 60 litres and the steam generated was used to drive a 2.5 HP steam pump. Adams' work is described in a book written by him entitled *Solar Heat—A Substitute for Fuel in Tropical Countries for Heating Steam Boilers and Other Purposes* (Education Society's Press, Byculla, Bombay, 1878).

The energy of the sun is collected by water flowing through the array of flat-plate collectors. In order to get the maximum possible temperature, booster mirrors which reflect radiation on to the flat-plate collectors are sometimes used. The hot water at temperatures close to 100°C is stored in a well-insulated thermal storage tank. From here, it flows through a vapour generator through which the working fluid of the Rankine cycle is also passed. The working fluid has a low boiling point. Consequently, vapour at about 90°C and a pressure of a few atmospheres leaves the vapour generator. This vapour then executes a regular Rankine cycle by flowing through a prime mover, a condenser and a liquid pump. The working fluids normally used are organic fluids like methyl chloride and toluene, and refrigerants like R-11, R-113 and R-114.

It has to be noted that the overall efficiency of this system is rather low, because the temperature difference between the vapour leaving the generator and the condensed liquid leaving the condenser is small. For the cycle shown in Fig. 2.19, the temperature difference is only 55°C. This leads to a Rankine cycle efficiency of 7 to 8 per cent. The efficiency of the collector system is of the order of 25 per cent. Hence an overall efficiency of only about 2 per cent is obtained.

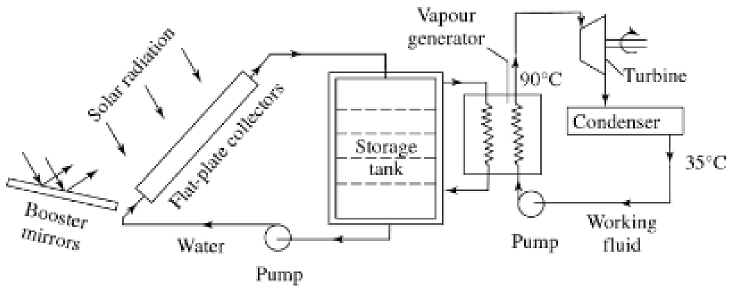

Fig. 2.19 *Low temperature power generation cycle using liquid flat-plate collectors*

Plants of this type, of French design, having generation capacities up to about 50 kW were installed in many parts of the world, particularly Africa, in the seventies. A 10 kW plant was also installed at IIT Madras in 1979–80 under an Indo-German collaboration agreement. However, such plants have been found to be very costly because of the large collector areas involved. Typically the installed cost is about Rs 300 000 per kW for 6 to 8 hours of daily operation, the main component of cost being the collectors.

In order to reduce the cost, solar ponds have been used instead of flat-plate collectors. The first two solar pond power plants having capacities of 6 kW and 150 kW were constructed in Israel about 30 years ago. These were followed in 1984 by the largest plant in the world at Beit Ha'aravah generating about 800 kW on a continuous basis. The working of these plants firmly established the technical viability of solar pond power plants. However they were also not found to be economically attractive in spite of being less costly than plants using flat-plate collector systems.

The concept of a *solar chimney power plant* was suggested in the 1970s. It is also called a solar updraft tower power plant. In such a plant, a tall central chimney is surrounded at its base by a circular greenhouse consisting of a transparent cover supported a few metres above the ground by a metal frame (Fig. 2.20). Sunlight passing through the transparent cover causes the air trapped in the greenhouse to heat up by 10° to 20°C. Thereby a convection system is set up in which the hot air is drawn up through the central chimney, and is continuously replenished by fresh air drawn in at the periphery of the greenhouse. The energy contained in the updraft air is converted into mechanical energy by turbines located at the base of the chimney and then into electrical energy by conventional electrical generators.

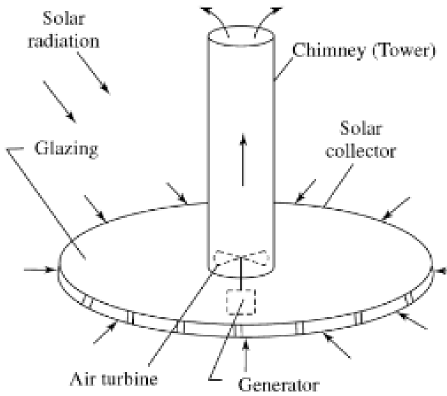

Fig. 2.20 *Solar chimney power plant*

The only solar chimney power plant built so far has been an experimental pilot plant in Manzanares, Spain. It had a 195 m high chimney with a constant diameter of 10.3 m. The solar collector area extended to a radius of 122 m from the chimney with the glazing being 1.85 m above the ground. The total area of the glazing was 46 000 m^2, 40 000 m^2 being plastic membrane and 6000 m^2 being glass. The turbine, housed at the base of the chimney, had four 5 m long blades and rotated at 1500 rpm to produce a peak output of 50 kW. Construction of the plant was completed in 1982 and it was operated up to 1989. The purpose was to demonstrate the operating principle and obtain operational data and experience on a long-term basis. From mid-1986 to early 1989 for a period of 32 months, the plant was run regularly on a daily basis. During this period, it operated fully automatically for an average of 8.9 hours every day and generated 44 MWh annually. The results obtained showed that the plant as a whole was capable of reliable operation over extended periods of time.

The energy conversion efficiency of a solar chimney is inherently low. It can be shown that the maximum possible efficiency is given by the expression [7]:

$$\eta_{\max} = \frac{g H}{C_p T_a} \tag{2.2.1}$$

where H = height of the chimney tower, and

T_a = temperature of the ambient air.

Equation (2.2.1) displays a basic characteristic of a solar chimney, viz. that the efficiency is directly proportional to the height. The equation is also useful for estimating the overall efficiency of a solar chimney power plant.

Example 2.2 *It is proposed to set up a solar chimney power plant in Rajasthan with a chimney 300 m high. Calculate the maximum possible conversion efficiency obtainable with the chimney. Also estimate the efficiency of the plant as a whole and the daily electrical output in a typical summer month (in kWh), if the solar collection area of the greenhouse is 50 000 m².*

Solution We will use Eq. (2.2.1). Substituting H = 300 m, C_p = 1005 J/kg-K and T_a = 305 K, we get

$$\eta_{\max} = \frac{9.81 \times 300}{1005 \times 305} = 0.00960, \text{ i.e. } 0.96\ \%.$$

Assume:

1. The turbine-generator set converts only 50 per cent out of the maximum available energy into electrical energy, and
2. The collection efficiency of the greenhouse is 25 per cent

Then

$$\eta_{\text{overall}} = 0.25 \times 0.00960 \times 0.50 = 0.0012, \text{ i.e. } 0.12\ \%.$$

The solar radiation on a typical summer day in May or June in Rajasthan may be taken as 6.5 kWh/m². Therefore, the daily electrical output of the plant

$$= 6.5 \times 50\ 000 \times 0.0012 = 390 \text{ kWh}$$

Example 2.2 shows that the overall energy conversion efficiency of a solar chimney power plant is low. Because of this fact, a small-capacity plant (in the kilowatt range) is not economically viable. One needs to build large capacity plants with very tall chimneys and large collector areas at the ground level to achieve economy with scale-up. Plans have been developed for building a 200 MWe plant in Australia. The design concept visualizes a chimney 1 km high and a greenhouse collector 7 km in diameter at the base [8].

Medium Temperature Systems Among solar thermal-electric power plants, those operating on medium temperature cycles and using the line-focussing parabolic collector technology at a temperature close to 400°C have proved to be the most cost effective and successful so far. A schematic diagram of a typical plant is shown in Fig. 2.21. The first commercial plant of this type (Solar Electric Generating System-SEGS I) having a capacity of 14 MW was set up in 1984. Since then six plants of 30 MW capacity each (SEGS II to VII), followed by two plants of 80 MW each (SEGS VIII and IX), were installed and commissioned. All these plants were set up by LUZ International in California, which has a total installed capacity of 354 MW. The collector array for SEGS IX has an area of 483 960 m^2. The cylindrical parabolic collectors used have their axes oriented north-south. The absorber tube used is made of stainless steel and has a specially developed selective coating. It is surrounded by a glass cover with a vacuum. The collectors heat a synthetic oil (Dowtherm A) to a temperature of 390°C with a collector efficiency of about 0.7 for beam radiation. The synthetic oil is used for generating superheated high pressure steam which executes a Rankine cycle with an efficiency of 38 per cent. The plant generally produces electricity for about eight hours a day and is coupled with natural gas for continuous operation. The installed cost of this type of plant has reduced over the years because of the increasing installed capacity. However it is very high. SEGS VIII which commenced operation in 1990 is reported to have cost $ 4000 per kW. Because of the high capital cost, no new large-size plants have been erected after 1991. However SEGS I – IX have continued to operate and valuable operating experience extending to more than 15 years has been obtained.

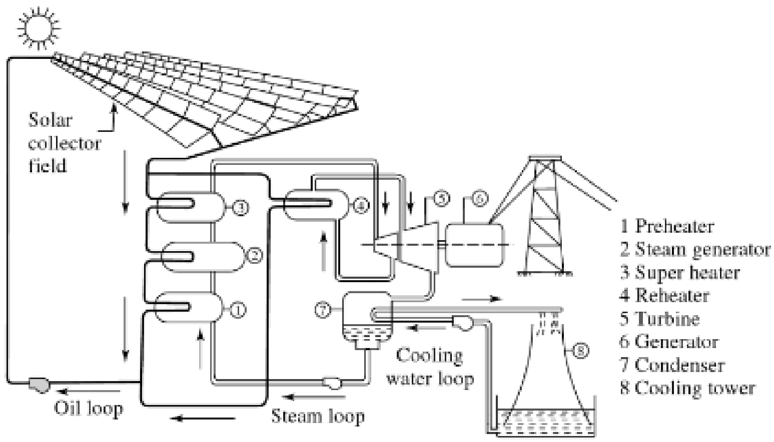

Fig. 2.21 *Medium temperature power generation cycle using cylindrical parabolic concentrating collectors*

Since the installation of the SEGS plants, significant advances have been made in parabolic collector technology as well as organic Rankine cycle technology. This has resulted in making smaller capacity plants more economically feasible. As a consequence, the Arizona Public Service Company has erected a 1 MWe plant at Red Rock, Arizona, USA in 2006. The plant has a line-focussing parabolic collector array with an area of 10 346 m^2 which heats a thermic fluid to a temperature of 300°C. The heat stored in the thermic fluid is used to operate an organic Rankine cycle which has n-pentane as its working fluid. The n-pentane vapour is at a pressure of 22.3 bar and a temperature of 204°C at the inlet to the turbine and yields a cycle efficiency of 20.7 per cent. The plant as a whole generates 2000 MWh annually. In addition to the Arizona plant, a 64 MWe solar power plant using parabolic collectors has been commissioned in June 2007 at Boulder City, Nevada, USA.

The Indian experience with the line-focussing parabolic collector technology has been restricted so far to a small 50 kW capacity experimental plant installed at the Solar Energy Centre of the Ministry of New and Renewable Energy. A project report for installing a parabolic collector power plant with a capacity of 30 MW in Rajasthan was also prepared. However, the project has not been executed.

Example 2.3 *Make suitable assumptions and estimate the collector area required for a 80 MWe line-focussing solar thermal power plant producing electricity for 8 hours every day.*

Solution We will make the following assumptions:

1. The collector is operating at a temperature of 400°C. At this temperature, the collector efficiency may be taken as 0.6 (refer to Fig. 2.6).
2. The Rankine cycle has an efficiency of 0.36.
3. The electrical generator efficiency is 0.96.
4. The solar insolation during a typical day is 6 kWh/m^2.

An energy balance over a day yields the following:

Solar radiation incident on the collectors per unit area per day × Collector area × Collector efficiency × Rankine cycle efficiency × Generator efficiency = Electricity production × Hours per day

$$6 \times A_c \times 0.6 \times 0.36 \times 0.96 = 80\ 000 \times 8$$

$$A_c = 514\ 403 \text{ m}^2$$

(*Note*: This value agrees reasonably well with the area of 483 960 m^2 used in SEGS IX.)

■

High Temperature Systems Two concepts have been experimented with in the case of high temperature systems. These are the paraboloid dish concept and the central receiver concept.

In the *paraboloid dish concept,* the concentrator tracks the sun by rotating about two axes and the sun's rays are brought to a point focus. A fluid flowing through a receiver at the focus is heated and this heat is used to drive a prime mover. Typically, Stirling engines have been favoured as the prime movers. For this reason, such systems are referred to as *Dish-Stirling Systems*. Because of the limitations on the size of the concentrator, paraboloid dish systems can be expected to generate power in kilowatts rather than megawatts. Thus they can be expected to meet the local power needs of communities, particularly in rural areas.

A few details about four systems developed for commercial applications are given in Table 2.1. It will be seen that the peak outputs range from 8.5 to 25.3 kW, while the peak net efficiencies range from 19 to 29.4 per cent.

Table 2.1 *Paraboloid dish systems*[+]

System name	Sun Dish	Euro Dish	SES	WGA
Location	USA	Spain	USA	USA
Rated output (kW)	22	10	25	9.5
Peak output (kW)	22.9	8.5	25.3	11.0
Peak net efficiency (%)	20	19	29.4	24.5
Area of reflecting glass (m^2)	117.2	60.0	91.0	42.9
Receiver aperture diameter (m)	0.38	0.15	0.20	0.14
Power cycle	Stirling	Stirling	Stirling	Stirling
Working fluid	Hydrogen	Helium	Hydrogen	Hydrogen

[+]Adapted from Mancini *et al.* [9].

Two important issues for commercialising Dish-Stirling systems are cost and reliability. Presently installation costs of such systems are very high, at around \$ 10 000 per kW. This is because very few systems have been built. However, it is estimated that the cost of a system could reduce to \$ 2500 per kW if there is a production of 500 units per year.

In a *central receiver system,* solar radiation reflected from an array of large mirrors is concentrated on a receiver situated at the top of a supporting tower. The mirrors are called *heliostats* and they are placed on the ground around the tower. Their orientation is individually controlled so that throughout the day they reflect beam radiation on the receiver. A fluid flowing through the receiver absorbs the concentrated radiation and transports the heat to the ground level where it is used to operate a thermodynamic cycle like the Rankine or the Brayton cycle. Molten salts, water (converted to steam) and air have been used as the heat transfer fluids. Because of the use of a receiver placed at the top of a tower, a central receiver system is also referred to as a power tower.

A schematic diagram of a typical central receiver system using a molten salt as the heat transfer fluid is shown in Fig. 2.22. The molten salt used frequently is a mixture of 60 per cent sodium nitrate and 40 per cent potassium nitrate. Cold salt at 290°C is pumped from a tank at ground level to the receiver at the top of a tower where it is heated by the concentrated radiation to a temperature of 565°C. The salt flows back to another tank at ground level. In order to generate electricity, hot salt is pumped from the hot tank through a steam generator where superheated steam is produced. The superheated steam then goes through a Rankine cycle to produce mechanical work and then electricity. The heliostat array can be sized to collect more power than is required by the electricity generation system. In that case, the excess thermal energy in the form of excess salt at 565°C accumulates in the hot tank and serves as a thermal storage.

Table 2.2 is a listing of nine central receiver systems built in the eighties and nineties. All of them were pilot plants with electrical outputs ranging from 0.5 to

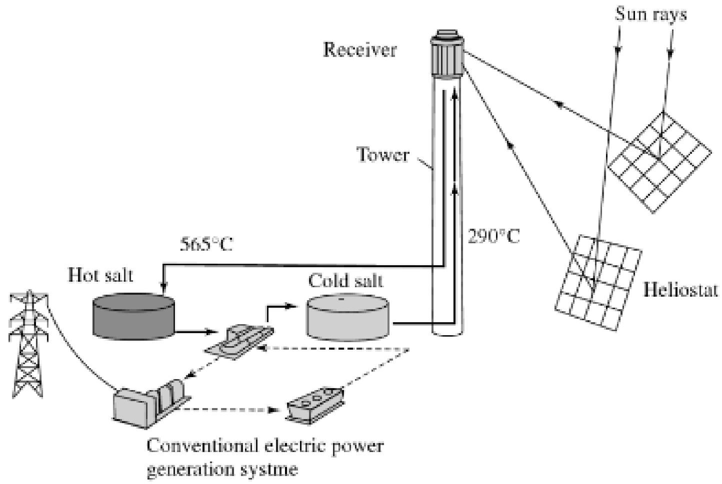

Fig. 2.22 *Central receiver system using a molten salt as the heat transfer fluid [10]*

10 MW and were built with the idea of demonstrating the viability of the concepts involved. A few details are given in Table 2.2*. These include the number and size of the heliostats, the receiver type, the receiver fluid, the thermal storage medium and the tower height.

Of the seven plants built in the eighties, the largest was Solar One at Barstow, California. Solar One had an external type, tubular receiver with sub-cooled water entering at the inlet and superheated steam at 102 bar and 510°C being delivered at the outlet. Most of the time, the steam was directly fed to a turbine which was part of a Rankine cycle. The plant was operated for six years from 1982 to 1988 and the feasibility of the power tower concept was successfully demonstrated. However, Solar One suffered from some problems. The receiver had a low collection efficiency and the tubes failed frequently because of the thermal stresses which they had to encounter in handling single phase liquid flow, two-phase flow and single phase vapour flow. Also the thermal storage system (which was an oil-rock system) was of inadequate capacity and operated only in a temperature range from 220° to 305°C, which was too low.

Because of the problems encountered during the operation of Solar One, it was decided to make modifications in some of the components. Molten salt was used as the heat transfer fluid instead of water/steam so that only single phase liquid flow occurred in the tubes of the receiver. In addition, a new molten salt thermal storage system with a larger capacity was installed instead of the oil-rock storage system and 108 heliostats (each having an area of 95 m^2) were

* More details of the collector systems in medium and high temperature solar power plants are given in Secs. 6.3, 6.5 and 6.6.

Table 2.2 *Solar central receiver power plants*

Plant name	SSPS	Eurelios	CESA I	Sunshine	Themis	CES 5	Solar One	TSA	Solar Two
Location	Spain	Italy	Spain	Japan	France	USSR	USA	Spain	USA
Output (MWe)	0.5	1	1.2	1	2	5	10	1	10
Number of heliostats	93	112, 70	300	807	201	1600	1818	300	1818, 108
Area of heliostat (m^2)	39.3	23, 52	39.6	16	53.7	25	39.3	39.6	39.3, 95
Total reflecting area (m^2)	3655	6216	11 880	12 912	10 740	40 000	71 447	11 880	81 707
Receiver type	Cavity	Cavity	Cavity	Cavity	Cavity	External	External	Cavity	External
Receiver fluid	Liquid sodium	Steam	Steam	Steam	Molten salt	Steam	Steam	Air	Molten salt
Thermal storage medium	Liquid sodium	Molten salt	Molten salt	Molten salt	Molten salt	Water	Oil/Rock	Ceramic	Molten salt
Tower height (m)	43	55	60	69	165	70	80	60	80
Start of operation	1981	1981	1983	1981	1983	1985	1982	1993	1996

added. The other hardware of Solar One was essentially reused. The modified plant was called Solar Two. It began operation in 1996 and was run for three years. The project successfully demonstrated the potential of molten salt technology and the associated thermal storage system.

The nineties also saw the testing of a central receiver system using air as the heat transfer fluid. This followed the development of cavity type, volumetric receivers. An open loop volumetric air receiver capable of absorbing 2.5 MW of heat was installed on top of the tower of the CESA-I plant which had earlier used a cavity-type tubular receiver to heat a molten salt. Some other modifications were also made and the modified plant called TSA was operated for six months in 1993 and again for a shorter period in 1994 and 1999. It was shown that a receiver outlet temperature of 700°C could be easily achieved and it was felt that the use of volumetric receiver air technology had been successfully demonstrated.

In the current decade, the only plant set up is PS 10 in Spain. Construction of the plant was completed in 2006 and commercial operation commenced in March 2007. Some details of the plant are as follows:

Output	: 10 MWe
Number of heliostats	: 624
Area of heliostat	: 120 m^2
Receiver fluid	: Water (converted into saturated steam at 40 bar)
Thermal storage medium	: Water
Tower height	: 115 m

Although all the central receiver systems described in Table 2.2 were operated successfully, the available data indicate that the construction costs were very high. For example, Solar One costed approximately $ 14 000 per kW. However, costs have reduced significantly because of improvements in design and the investment cost of the latest plant PS 10 is reported to be 3500 Euro ($ 4590) per kW. Initial investment costs are likely to reduce further with more operational experience and scale-up in the output.

2.2.5 Distillation

In many small communities, the natural supply of fresh water is inadequate in comparison to the availability of brackish or saline water. Solar distillation can prove to be an effective way of supplying drinking water to such communities.

The principle of solar distillation is simple and can be explained with reference to Fig. 2.23, in which a conventional basin-type solar still is shown. The still consists of a shallow air-tight basin lined with a black, impervious material which contains the saline water. A sloping transparent cover is provided at the top. Solar radiation is transmitted through the cover and is absorbed in the black lining. It thus heats up the water by about 10° to 20°C and causes it to evaporate. The resulting vapour rises, condenses as pure water on the underside of the

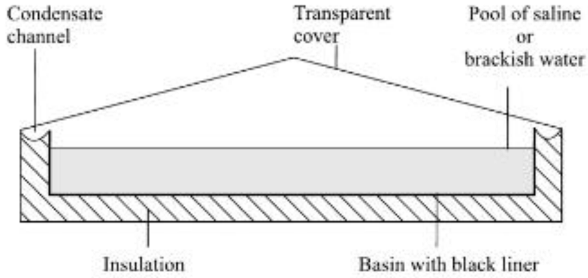

Fig. 2.23 *Solar still*

cover and flows into condensate collection channels on the sides. An output of about 3 litres/m^2 with an associated efficiency of 30 to 35 per cent can be obtained in a well-designed still on a good sunny day.

A number of basin-type solar-still plants having areas greater than 100 m^2 are in operation in many parts of Africa and the West Indies.

2.2.6 Drying

One of the traditional uses of solar energy has been for drying of agricultural products. The drying process removes moisture and helps in the preservation of the product. Traditionally, drying is done on open ground. The disadvantages associated with this are that the process is slow and that insects and dust get mixed with the product. The use of dryers help to eliminate these disadvantages. Drying can then be done faster and in a controlled fashion. In addition, a better-quality product is obtained.

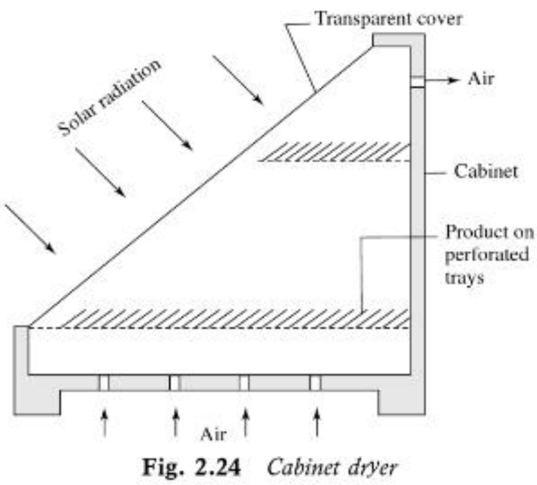

Fig. 2.24 *Cabinet dryer*

A cabinet-type solar dryer, suitable for small-scale use, is shown in Fig. 2.24. The dryer consists of an enclosure with a transparent cover. The material to be dried is placed on perforated trays. Solar radiation entering the enclosure is absorbed in the product itself and the surrounding internal surfaces of the enclosure. As a result, moisture is removed from the product and the air inside is heated. Suitable openings at the bottom and top ensure a natural circulation. Temperatures ranging from 50°C to 80°C are usually attained and the drying time ranges from 2 to 4 days. Typical products which can be dried in such devices are dates, apricots, chillies, grapes, etc.

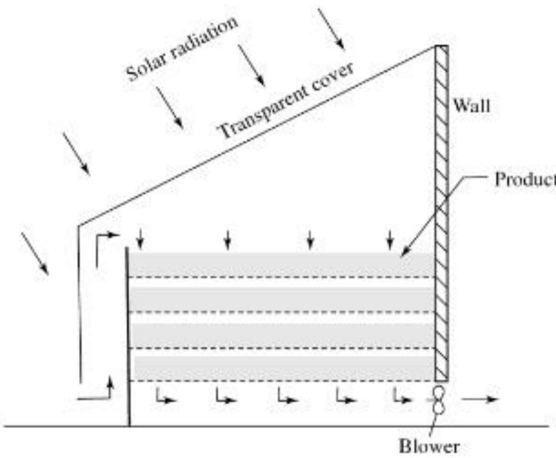

Fig. 2.25 *Forced circulation dryer (direct gain)*

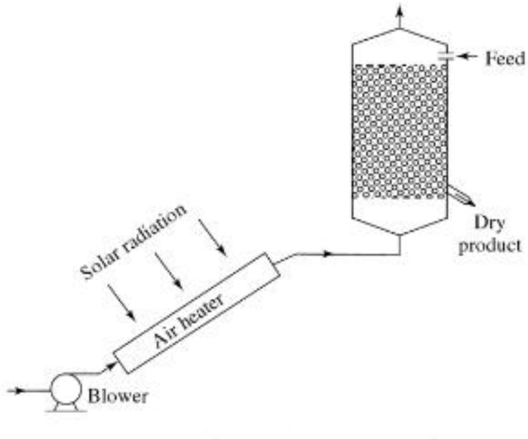

Fig. 2.26 *Forced circulation dryer (indirect gain)*

For large-scale drying, the passive device of Fig. 2.24 relying on natural circulation is replaced by an active device with forced circulation as shown in Fig. 2.25. Systems of this type have been used for drying timber.

An indirect type of active device is used when the solar radiation falling directly on the product (as in Figs 2.24 and 2.25) is not adequate, or the temperature of the product needs to be controlled. One such system is shown in Fig. 2.26. Here, the air is heated separately in an array of solar air heaters and then ducted to the chamber in which the product to be dried is stored. Such dryers are suitable for food grains, tea, spices, etc. and for products like leather and ceramics. An 11 m^2 solar air heating system installed in Cuddallore, Tamil Nadu for drying fish is shown in Plate 2.4.

In India about 10 000 m^2 of collector area for drying various kinds of crops and food products, and for drying timber has been installed so far in about 50 industries. The specifications of a typical industrial drying system which has been used since 1995 in a spice powder manufacturing company in Theni, Tamil Nadu for drying chillies and coriander seeds are given below [11]. The solar system is an add-on to an existing dryer, which is run with firewood. The firewood dryer has been kept as a stand-by unit.

Collector array	: Roof mounted air heaters with an area of 290 m^2
Collector	: Single glazed, corrugated aluminium absorber with matt black paint (Air flows between the cover and the absorber.)
Typical temperature rise	: 30°C
Type of dryer	: Tunnel (continuous drying)
Material dried	: Chillies
Initial moisture content	: 11 to 14%
Moisture content after drying	: About 5%
Capacity	: 10 t/day

2.2.7 Cooking

An important domestic thermal application is that of cooking. Over the past 40 years, a number of designs of solar cookers have been developed, a few of which are described here.

Solar cooker designs generally fall into one of two categories. One category is the box-type cooker, a slow cooking device suitable for domestic purposes. It essentially consists of a rectangular enclosure insulated on the bottom and sides, and having one or two glass covers on the top. Solar radiation enters through the top and heats up the enclosure in which the food to be cooked is placed in shallow vessels. A typical size available has an enclosure about 50 cm square and 12 cm deep. Temperatures around 100°C can be obtained in these cookers on sunny days and pulses, rice, vegetables, etc., can be readily cooked. The time taken for cooking depends upon the solar radiation and varies from half an hour to two and a half hours.

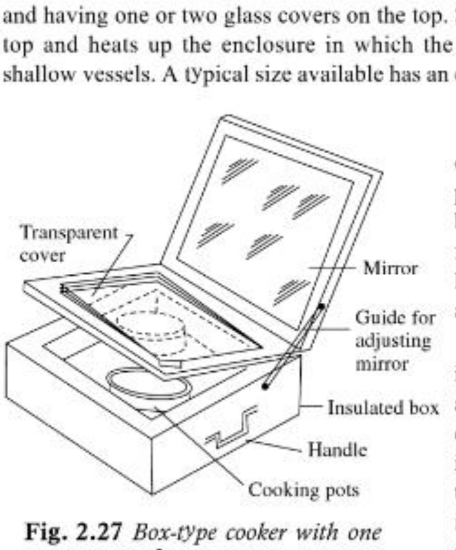

Fig. 2.27 *Box-type cooker with one reflector*

A single glass reflector whose inclination can be varied is usually attached to the box-type cooker. A sketch of such a cooker is shown in Fig. 2.27. The addition of the mirror helps in achieving enclosure temperatures which are higher by about 15° to 20°C.

As a result, the cooking time is reduced. Cookers with reflectors on all four edges have also been built.

Box-type cookers with no reflector or with one reflector are simple to use and require little attention. As a result, they have found the maximum acceptance amongst all the designs developed. The item to be cooked has only to be placed inside and taken out, so that with some experience, the operator does not have to spend much time in the sun. However, the disadvantage is that they cannot be used for cooking items like *chapatis* and *purees* since these require higher temperatures.

Box-type cookers are being made by many manufacturers in India. The cost of a typical good quality cooker with a mirror varies from Rs 1000 to 2500. In most places in India, such cookers can be used for at least 250 days in the year and it is estimated that the cost of a box-type cooker is recovered within a period of three to four years. Because of the relatively low payback period, solar cookers have become fairly popular. It is estimated that more than 600 000 cookers have been sold so far and the number is growing at the rate of about 20 000 to 30 000 every year.

The second category of solar cookers developed are those in which the radiation is concentrated by a paraboloid reflecting surface. The cooking vessel is placed at the focus of the paraboloid mirror and is thus directly heated. The dimensions, specifications and cost of a typical cooker are as follows:

Aperture diameter	: 1.4 m
Focal length	: 0.28 m
Reflecting surface	: Anodized aluminium sheet
Cost	: Rs 3500 to 5000

This cooker is referred to as a dish solar cooker. Temperatures well above 200°C are obtained in it and it can be used for cooking food items requiring roasting, frying or boiling. The disadvantage of a dish cooker is that it requires manual tracking every 15 or 20 minutes. Also, since the cooking is done outdoors, the operator has to spend a considerable amount of time in the sun.

A variation of the paraboloid-type cooker has been developed by Scheffler [12] such that solar radiation can be concentrated and brought inside the kitchen. The reflector is a small lateral section of a much larger paraboloid. The inclined cut produces the typical shape of the Scheffler reflector. The reflector usually consists of a number of mirror facets supported by a steel frame. It is mounted outside the kitchen facing south (in the northern hemisphere). It reflects the solar rays through an opening in the north wall of the kitchen on to a secondary reflector inside the kitchen. The secondary reflector further concentrates the rays on to the bottom of the cooking vessel (Fig. 2.28). These cookers require tracking such that the focus stays fixed. The daily rotation is generally carried out by a mechanical tracking device (clock work). In addition, every second or third day, the tilt of the reflector is adjusted and the reflector is flexed so that most of the solar rays are reflected to the secondary reflector. Temperatures as high as 400°C can be attained and all types of cooking/frying are possible. One need not have to go outside in the sun unlike a normal paraboloid cooker. Cooking for about 40 to 50 persons is possible with this cooker. Four sizes (7.4, 9.5, 12.5 and 16 m^2) of Scheffler reflectors are available commercially in India.

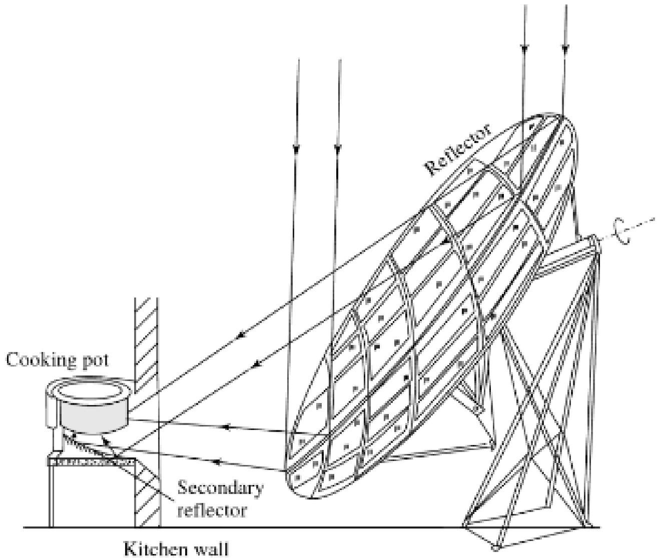

Fig. 2.28 *Schematic diagram of a Scheffler cooker [11]*

The Scheffler cooker is useful for institutional kitchens, hotels, etc. The typical cost of such a cooker is about Rs 40 000 and it yields a saving of 35 to 40 LPG cylinders per year [13]. A series of such cookers can also be used to generate steam which can be used for cooking. Such installations have been made at a few places in India. It may be mentioned that Scheffler reflectors are also used to provide low pressure steam for industrial applications [14, 15].

The world's largest steam cooking system based on Scheffler reflectors has been installed at Tirumala Tirupathi Devasthanam, Andhra Pradesh (Plate 2.5). The specifications of the system are as follows:

Capacity	: Food for 15 000 persons per day
Number of reflectors	: 106; each of 9.2 m^2 area
Reflector material	: Acrylic mirror
Output	: 4000 kg of steam per day at 180°C and 10 bar

A unique solar cooker using a fixed bowl with a moving receiver has been developed and installed at the Centre for Scientific Research, Pondicherry [16] (Plate 2.6). It consists of a large spherical bowl concentrator integrated into the kitchen roof using prefabricated ferrocement curved channels. Laminated mirror pieces, 15 cm × 15 cm in size, have been fixed using silicone and act as the reflecting surface. The aperture area of the spherical reflector is 176 m^2. The receiver is suspended over the collector from a single support pipe and is rotated about a polar axis. It consists of a long coil of MS pipes wrapped around a steel frame. Water is pumped through the coil to generate steam which is taken to the kitchen and used for cooking purposes. The typical peak thermal energy output recorded is 63 kW. This corresponds to a steam production of 86 kg/h.

2.3 SOME OBSERVATIONS

It will be useful to conclude this chapter with some observations. Our survey of various solar thermal applications shows that water heating systems for domestic as well as industrial purposes have already made a small and encouraging impact on the Indian energy scene. The same is true of the box-type solar cooker. In fact, India now has the distinction of having the largest number of solar cookers amongst all the countries of the world.

Other applications using heat directly like space heating and drying of agricultural products have not yet made the same impact. This is a little surprising because they have a definite, important role to play in certain regions or for specific purposes. For example, space heating by passive methods if integrated into the initial design of a building can be very beneficial in the northern parts of India. Similarly, there is good scope for solar drying. Solar distillation too has an important role to play in meeting the needs of thousands of small communities across the country where drinking water is scarce. Unfortunately it is hardly being used. A concerted effort has to be made to make all these technologies more cost effective and reliable, and to disseminate information regarding their use.

As far as solar thermal power generation is concerned, it has to be recognized that solar thermal energy can make a real impact if it leads to large scale cost-effective electrical power generation. Our survey of the world scene shows that although this is far from being the case, impressive developments have taken place in the last two decades. Medium temperature systems using line-focussing parabolic collector technology have been commercialized to some extent. Also, the central receiver concept has been tested extensively on a pilot scale and the solar chimney concept has been proved. Both systems seem promising, but need a considerable amount of developmental work before their suitability and viability can be assessed.