Module-2

Solar Thermal Energy Collectors: Types of Solar Collectors, Configurations of Certain Practical Solar Thermal Collectors, Material Aspects of Solar Collectors, Concentrating Collectors, Parabolic Dish – Stirling Engine System, Working of Stirling or Brayton Heat Engine, Solar Collector Systems into Building Services, Solar Water Heating Systems, Passive Solar Water Heating Systems, Applications of Solar Water Heating Systems, Active Solar Space Cooling, Solar Air Heating, Solar Dryers, Crop Drying, Space Cooing, Solar Cookers, Solar pond.
Solar Cells: Components of Solar Cell System, Elements of Silicon Solar Cell, Solar Cell materials, Practical Solar Cells, I – V Characteristics of Solar Cells, Efficiency of Solar Cells, Photovoltaic panels (series and parallel arrays).

The material from this is prepared only for educational use from various text books and material from internet.

Suggested Learning Resources:
Text Books 1. Nonconventional Energy sources, G D Rai, Khanna Publication, Fourth Edition,
2. Energy Technology, S.Rao and Dr. B.B. Parulekar, Khanna Publication Solar energy, Subhas P Sukhatme, TataMcGrawHill, 2nd Edition,1996.
3. Principles of Energy conversion, A. W. Culp Jr., McGraw Hill, 1996
4. Non-Convention Energy Resources, Shobh Nath Singh, Pearson, 2018

Questions:

1. With a neat sketch, discuss the important parts of a flat plate collector and the material aspects.
2. What are the advantages and disadvantages of concentrating collectors over a flat plate collector?
3. Classify the different solar thermal collectors?. Write in short the working of parabolic solar thermal collector
4. With a neat diagram, explain the working of solar cooker.
5. Explain the working of sterling heat engine with the help of neat sketch
6. Explain the applications of solar thermal energy for crop drying
7. With a neat diagram, explain the solar pond and write any one advantage of it.
8. Give a brief account of solar space heating and differentiate passive and active space heating.
9. What are the different types of solar thermal systems used for energy generation, and how do they differ in their design and operation?
10. Explain the principle of the solar photovoltaic cell.
11. What are the advantages, limitations and applications of solar photovoltaic system
12. Draw and explain the electrical equivalent circuit model and current-voltage characteristics of solar cell. Discuss the efficiency of solar cell
13. Explain the principle of solar PV power generation. What are the main parts of solar PV system
14. How PV can be integrated to power grid, explain

Introduction

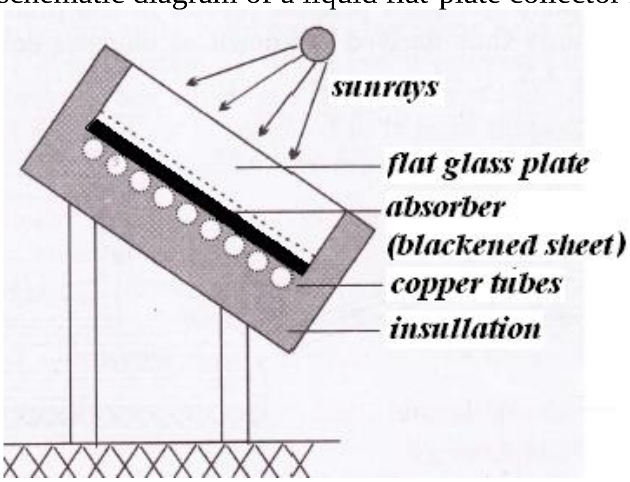
Sun's heat energy is a diffuse energy. It is always first collected and then concentrated. In residential systems, simple and cheap solar panels are used to collect the solar heat energy below 60°C. Residential panels for heat collection are referred to as flat plate collectors. In utility scale systems, solar heat energy is required to be concentrated at high temperature level in the range 70°C–80°C at the collectors. The utility panels are, therefore, called concentrators.

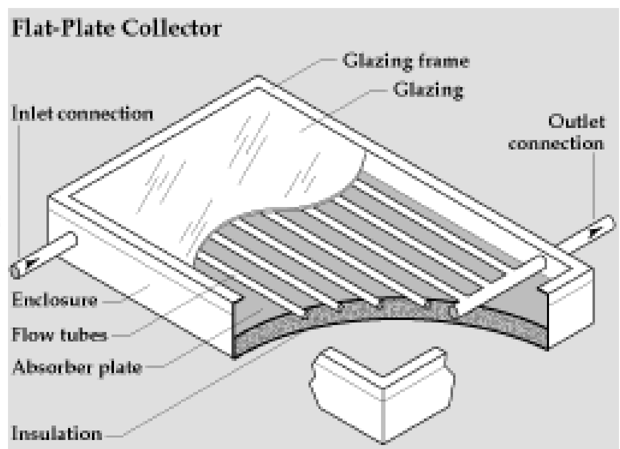
The solar collector absorbs the incoming solar radiation, converts it into heat, and then transfers this heat to a fluid (usually air, water, or oil) flowing through the collector.

TYPES OF SOLAR COLLECTORS

The collectors that are being marketed to utilize thermal energy from the sun can be subdivided into the following categories.

1 Flat Plate Collectors: Flat plate collectors are the most common type. They are also referred to as non- concentrating collectors and have the same area for intercepting and for absorbing solar radiation. A schematic diagram of a liquid flat-plate collector is shown in figure.





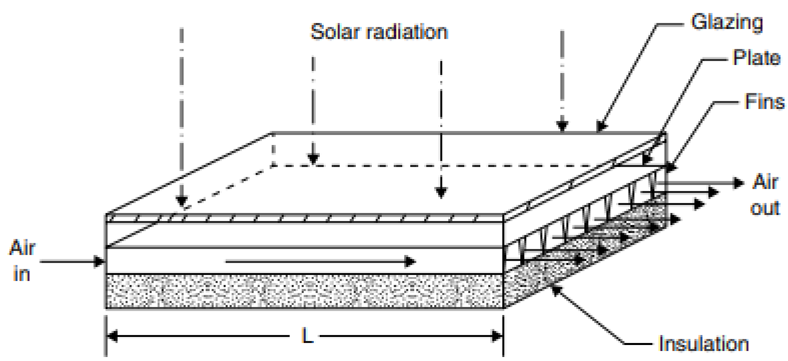
It has five important parts:

1. Dark flat plate absorber of solar energy: The absorber consists of a thin absorber sheet (of thermally stable polymeric materials such as aluminium, steel, or copper to which a black or selective coating is applied) because of the fact that the metal is a good heat conductor. Copper is more expensive, but is a better conductor and less prone to corrosion than aluminium. In locations with average availability of solar energy, flat plate collectors are sized approximately 0.5 to 1 square foot per gallon of daily hot water use.
2. Transparent cover: This allows solar energy to pass through, but reduces heat losses.
3. Heat-transport fluid (air, antifreeze, or water): To remove heat from the absorber, fluid is usually circulated through tubing to transfer heat from the absorber to an insulated water tank.
4. Heat insulation backing: Often backed by a grid or coil of fluid tubing.
5. Insulated casing: It is made of a glass or polycarbonate cover.

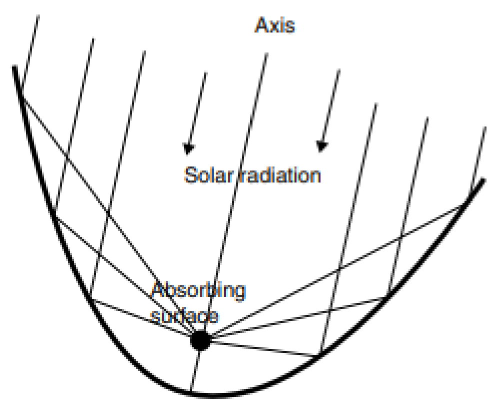
- ❖ In flat plate collectors, the incident solar rays are absorbed by its surface. Hence, it is called as the nonconcentrated type. Eg. Solar water heater panels, solar cooker panels etc.
- ❖ The solar radiation passes through a transparent cover made of glass and falls on an absorber plate.
- ❖ The absorber plate is painted black hence it acts as black body and absorbs solar radiation
- ❖ The transparent cover helps in reflecting the incident solar energy on to the absorber plate.

- Copper tubes are fixed to the absorber plate.
- The heat energy absorbed by the absorber plate is transferred to the cold water circulated through copper tubes
- The water gets heated and can be used for various purposes.
- The solar collector is usually insulated to avoid heat loss.
- Flat-plate collectors are used for a variety of applications in which temperatures ranging from 40°C to about 100°C are required.

1 Flat Plate Air Collectors Schematic arrangement of a typical flat plate air collector is shown in Figure. It uses air as the heat transport medium. Air flat plate collectors are used mainly for solar space heating. The absorber plates can be made of metal sheets, layers of screen, or non-metallic materials. The air flows past the absorber by using natural convection or a fan. Since air does not conduct heat as easily as liquid, air collectors are typically less efficient than liquid collectors.



2 Concentrating Collectors By using reflectors to concentrate sunlight on the absorber of a solar collector, the size of the absorber can be dramatically reduced, which reduces heat losses and increases efficiency at high temperatures. Another advantage is that reflectors can cost substantially less per unit area than collectors. This class of collector is used for high-temperature applications such as steam production for the generation of electricity and thermal detoxification. These collectors are best suited to climates that have an abundance of clear sky days, and therefore, they are not so common in many regions. Stationary concentrating collectors may be liquid-based, air-based, or even an oven such as a solar cooker. One such collector is a parabolic dish reflector, which is shown in Figure.



1 Stationary Concentrating Collectors These collectors are operated in a stationary mode for applications like air conditioning. Stationary concentrating collectors use compound parabolic reflectors and flat reflectors for directing solar energy to an accompanying absorber or aperture through a wide acceptance angle. The wide acceptance angle for these reflectors eliminates the need for a sun tracker. This class of collector includes parabolic trough flat plate collectors, flat plate collectors with parabolic boosting reflectors, and solar cookers. The development of the first two collectors has been done in Sweden. Solar cookers are used throughout the world, especially in the developing countries.

2 Tracking Concentrating Collectors In the case of high temperature applications, like solar electric generation tracking, the sun is necessary. Heliostats are tracking mirrors that reflect solar energy onto a fixed target.

CONFIGURATIONS OF CERTAIN PRACTICAL SOLAR THERMAL COLLECTORS

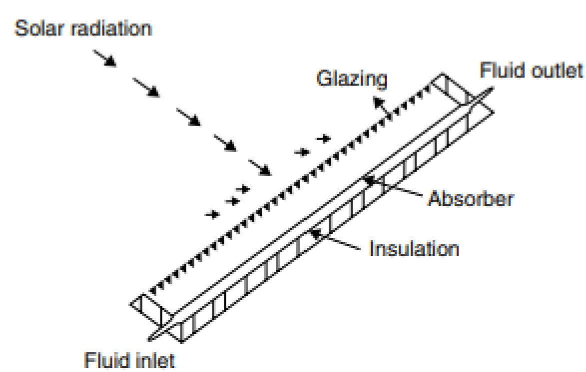
Undoubtedly, there are many different ways that solar energy can be applied, but there are also many different methods for collecting the solar energy from incident radiation. The following are the list of some popular types of solar collectors.

1 Flat Plate Collectors Flat plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-coloured absorber plate. These collectors heat liquid or air at temperatures less than 90°C. Flat plate collectors are used for residential water heating and space heating installations.

1.1 Liquid Flat Plate Collectors Liquid-based collectors use sunlight to heat a liquid that is circulating in a ‘solar loop’. The fluid in the solar loop can be water, an antifreeze mixture, thermal oil, etc. The solar loop transfers the thermal energy from the collectors to a thermal storage tank. The simplest liquid systems use potable household water, which is heated as it passes directly through the collector and then flows to the house. The type of collector selection depends on how hot the water must be and the local climate. Unglazed collectors are typically used for swimming pool heating.

1.2 Air Flat Plate Collectors These are used primarily for solar space heating. The absorber plates in air collectors can be metal sheets, layers of screen, or non-metallic materials. The air flows past the absorber by using natural convection or a fan. Because air conducts heat much less readily than liquid does, less heat is transferred from an air collector’s absorber than from a liquid collector’s absorber, and air collectors are typically less efficient than liquid collectors. The thermal energy collected from air-based solar collectors can be used for ventilation, air heating, space heating, and crop drying.

2 Glazed Flat Plate Collectors Glazed flat plate collectors are shown in Figure. They are very common and are available as liquid-based and air-based collectors. These collectors are better suited for moderate temperature applications where the demand temperature is 30°C–70°C and for applications that require heat during the winter months. The liquid-based collectors are most commonly used for the heating of domestic and commercial hot water, buildings, and indoor swimming pools. The air-based collectors are used for the heating of buildings, ventilation air, and crop drying



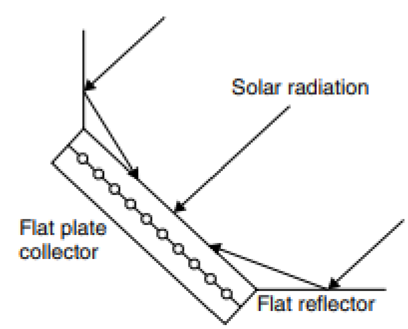
3 Unglazed Flat Plate Solar Collectors Unglazed flat plate collectors account for the larger proportion of collector installed per year of any type of solar collector in many countries. Because they are not insulated, these collectors are best suited for low temperature applications where the temperature demand is below 30°C. By far, the primary market is for heating outdoor swimming pools, but other markets exist including heating seasonal indoor swimming pools, pre-heating water for car washes, and heating water used in fish farming operations. There is also a market potential for these collectors for water heating at remote and seasonal locations like summer camps. Unglazed flat plate collectors are usually made of black plastic that has been stabilized to withstand ultraviolet light. Since these collectors have no glazing, a large portion of the sun's energy is absorbed. However, because they are not insulated, a large portion of the heat absorbed is lost, particularly when it is windy and not warm outside. They transfer heat so well to air (and from air) that they can actually 'capture' heat during the night when it is hot and windy outside.

4 Unglazed Perforated Plate Collectors The key to this type of collector is an industrial grade siding or cladding that is perforated with many small holes at a pitch of 2–4 cm. Air passes through the holes in the collector before it is drawn into the building to provide preheated fresh ventilation air. Efficiencies are typically high because the collector operates close to the outside air temperature. These systems can be very cost effective, especially when they replace conventional cladding on the building because only incremental costs need be compared to the energy savings. The most common application of this collector is for building ventilation air heating. Other possible components for this system are: a 20–30 cm air gap between the buildings, a canopy at the top of the wall that acts as a distribution manifold, and bypass dampers so that air will bypass the system during warm weather. Another application for this collector is crop drying. Systems have been installed in South America and Asia for drying of tea, coffee beans, and tobacco.

5 Back-pass Solar Collectors Air-based collectors use solar energy to heat air. Their design is simple and they often weigh less than liquid-based collectors because they do not have pressurized piping. Air-based collectors do not have freezing or boiling problems. In these systems, a large solar absorber is used to heat the air. The simplest designs are single-pass open collectors. Collectors that are coated with a glaze can also be used to heat air for space heating.

6 Batch Flat Plate Solar Thermal Collectors In ancient days, water tanks that were painted black were used as simple solar residential water heaters. Today, their primary market is for residential water heating in warm countries. Modern batch collectors have a glazing that is similar to the one used on flat plate collectors and/or a reflector to concentrate the solar energy on the tank surface. Because the storage tank and the solar absorber act as a single unit, there is no need for other components. On an area basis, batch collector systems are less costly than glazed flat plate collectors but also deliver less energy per year.

7 Flat Plate Collectors with Flat Reflectors It is found that the addition of reflector on collector increases the solar yield on the collector and the overall thermal performance of the collector. The enhancement in the solar yield on the collector is about 44% in winter and 15% in summer conditions, which is consistent with more hot water demand in winter. A variation of flat plate collector is shown in Figure.This simple reflector can markedly increase the amount of direct radiation reaching the collector. This is in fact a concentrate because the aperture is larger than the absorber plate.



8 Evacuated Tube Collectors Conventional simple flat plate solar collectors were developed for use in sunny and warm climatic conditions. However, their benefits are greatly reduced when conditions become unfavourable during cold, cloudy, and windy days. Furthermore, weathering influences such as condensation and moisture will cause early deterioration of internal materials resulting in reduced performance and system failure. Evacuated heat pipe solar collectors (tubes) operate differently than the other collectors available on the market. These solar collectors consist of a heat pipe inside a vacuum-sealed tube, as shown in Figures. Evacuated tube collectors can achieve extremely high temperatures (75°C–180°C), making them more appropriate for cooling applications and for commercial and industrial applications. However, evacuated tube collectors are more expensive than flat plate collectors, as their unit area costs about twice than that of the latter. Evacuated tube collectors are efficient at high temperatures.

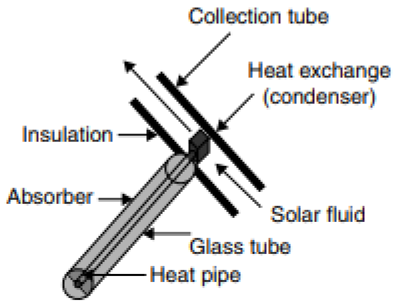


Figure Typical evacuated tube solar collectors

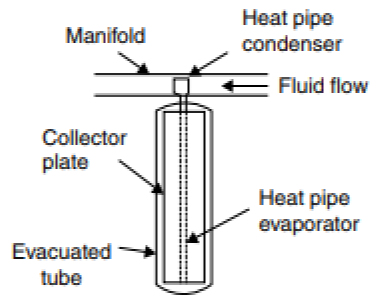


Figure Schematic evacuated tube solar collectors

MATERIAL ASPECTS OF SOLAR COLLECTORS

Flat, corrugated, or grooved plates, to which the tubes, fins, or passages are attached. The plate may be integrated with the tubes.

1 Absorber The following are the types of solar flat plate absorbers that are most frequently used. 1. all copper plates are with integrated water passage (roll bond type). These plates can also be made of aluminium. 2. all copper (copper tube on copper sheet). 3. copper tube or aluminium fin 4. iron or steel 5. plastic (polymers)

Absorptive Coatings

Many varieties of absorptive coating are being used, ranging from flat black paint to baked enamel. Flat black absorber coatings have high absorptivity.

Specification requirement of an absorber coating for a flat plate collector is as follows:

1. It must not degrade under ultraviolet exposure.
2. It must withstand temperature up to 200° C.
3. It must withstand many temperature cycles over ±40° C.
4. It must withstand many cycles of low to high relative humidity.
5. It must not chalk, fade, or chip.
6. It must not be so thick that heat conduction through the paint to the metal absorber is impeded.

2 Glazing

One or more sheets of glass or other diathermanous (radiation transmitting) material is used as transparent covers. Following are its important functions:

1. It must reduce convective losses from the absorber plate.
2. It must suppress radiative heat losses from the absorber plate.
3. It must protect the absorber from the elements and from excessive UV exposures. A glazing material must be resistant to UV radiation.

Glass meets the entire abovementioned requirements and also compatible with the general requirement of longevity.

The following are the specification requirement of glazing materials:

1. They must be reasonably impact resistant.
2. Thin or no tempered glass panes are questionable because of the risk of damage from hail, birds, and vandalism.
3. Plastic materials of low tensile strength (i.e., Teflon) are not advisable.
4. They must be resistant to significant temperature shock.

5. Sudden rain will cause rapid overall limb changes. A leaf on a stagnant collector can cause high localized thermal stresses.

Thus, heat tempered glass is absolute necessity for outer collector glazing. Generally, plastic glazing can easily withstand the temperature shocks. Non-UV inhibited plastic materials are not acceptable. Teflon (high transmittivity) and polyvinyl fluoride (PVF, Tedlar) are known to withstand UV radiation and is often used to protect other materials underneath from UV radiation.

Glazing Materials

1. Glass and fiberglass meet these requirements.
2. Tedlar used alone cannot serve the purpose.
3. Tedlar when bonded to the fiberglass, it acts as a good glazing material.
4. Optical rating must not change during its service life.
5. This requirement can hardly be met by any plastic glazing materials.
6. Fiberglass partially serves the purpose.

3 Insulation Shell

A solar flat plate collector must be insulated against excessive heat losses on its back side and on its edges as follows:

1. Back side – 3.5 inch of fiberglass insulation or 2 inch of foam insulation.
2. Side – 1 inch of fiberglass or 0.5 to 0.75 inch of foam insulation.

The following are the specifications to be met by insulating materials

1. It must withstand the maximum collector stagnation temperature rating (200°C) without damage. Foam materials shrink due to excessive heat.
2. The maximum stagnation temperature must not cause evaporation or sublimation of substances in the insulating materials such as the binder of the fiberglass.

Special fiberglass materials are available that have quite satisfactory outgassing rate.

CONCENTRATING COLLECTORS

They usually have concave reflecting surface to intercept and focus the sun's beam radiation to a smaller receiving area, thereby increasing the radiation flux. In other words, concentrating solar collectors use shaped mirrors or lenses to provide higher temperatures than the flat plate collectors.

However, each method of concentration has following drawbacks:

1. The mirror requires a clean smooth reflecting surface, because dust particles could scatter light away from the receiver or the light could be partly absorbed by a thin dirty film.
2. Smooth surface because contour error can also result in missing the receiver.

One criterion for the selection of a specific concentrator is the degree of concentration and hence temperature that is to be achieved. As a rule, concentrating energy on a point produces high to very high temperature; while on a line, it produces moderate to high temperature. Non-focusing concentrators produce low to moderate temperature.

Concentrating collectors are of various types and can be classified in many ways. They may be as follows:

1. Based on means of concentration: reflecting type use mirrors or refracting type use Fresnel lenses.
2. Based on reflecting surfaces used: parabolic, spherical, or flat.
3. Continuous or segmented.
4. Based on the formation of the image: imaging or non-imaging.
5. Imaging concentrator may focus on a line or at a point.
6. On the basis of collector concentration ratio or operating temperature range.

7. By the type of tracking

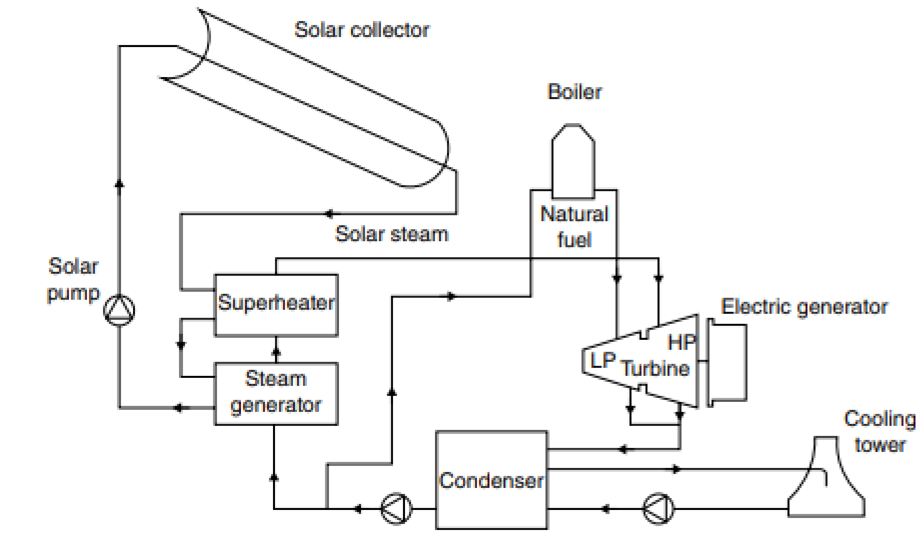
PARABOLIC DISH–STIRLING ENGINE SYSTEM

The major parts of a parabolic dish–Stirling engine system are as follows:

1. Solar dish concentrator: Parabolic dish systems that generate electricity from a central power converter collect the absorbed sunlight from individual receivers and deliver it via a heat-transfer fluid to the power conversion systems. The need to circulate heat-transfer fluid throughout the collector field raises design issues such as piping layout, pumping require ments, and thermal losses.
2. Power conversion unit: The power conversion unit includes the thermal receiver and the heat engine. The thermal receiver absorbs the concentrated beam of solar energy, converts it to heat, and transfers the heat to the heat engine. A thermal receiver can be a bank of tubes with a cooling fluid circulating through it. The heat transfer medium usually employed as the working fluid for an engine is hydrogen or helium. Alternate thermal receivers are heat pipes wherein the boiling and condensing of an intermediate fluid are used to transfer the heat to the engine. The heat engine system takes the heat from the thermal receiver and uses it to produce electricity. The engine–generators have several components; a receiver to absorb the concentrated sunlight to heat the working fluid of the engine, which then converts the thermal energy into mechanical work; an alternator attached to the engine to convert the work into electricity, a waste-heat exhaust system to vent excess heat to the atmosphere, and a control system to match the engine operation to the available solar energy. This distributed parabolic dish system lacks thermal storage capabilities, but can be hybridized to run on fossil fuel during periods without sunshine. The Stirling engine is the most common type of heat engine used in dish–engine systems.
3. Tracking system: A parabolic dish system uses a computer to track the sun and concentrate the sun's rays onto a receiver located at the focal point in front of the dish. In some systems, a heat engine, such as a Stirling engine, is linked to the receiver to generate electricity. Parabolic dish systems can reach 1,000 °C at the receiver, and achieve the highest efficiencies for converting solar energy to electricity in the small-power capacity range.

WORKING OF STIRLING OR BRAYTON HEAT ENGINE

After the array of mirrors focuses the sunlight, the concentrated sunlight then heats up the working fluid to temperatures of around 750°C within the receiver. The heated high temperature working fluid is then used in either a Stirling or Brayton heat engine cycle to produce mechanical power via otational kinetic energy and then electricity for utility use with an electric generator. An example of a Brayton cycle used to produce electricity for a parabolic dish power plant. In the cycle, the concentrated sunlight focused on the solar fluid heats up the com pressed working fluid of the cycle, i.e., air, replacing altogether or lowering the amount of fuel needed to heat up the air in the combustion chamber for power generation. As with all Brayton cycles, the hot compressed air is then expanded through a turbine to produce rotational kinetic energy, which is converted to electricity using the alternator. A recuperator is also utilized to capture waste heat from the turbine to preheat the compressed air and make the cycle more efficient.



SOLAR COLLECTOR SYSTEMS INTO BUILDING SERVICES

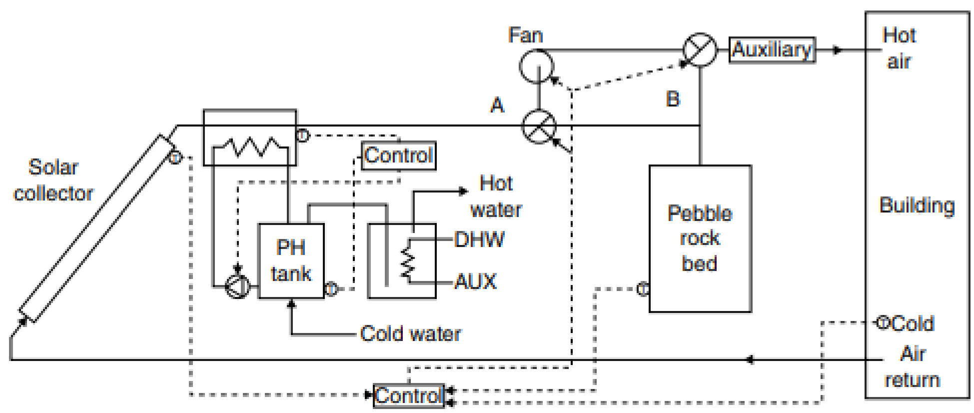
Although the operating costs of solar energy conversion system are generally low, the initial cost of purchasing and installing such system are high when compared to fossil fuel or other conventional energy system. Hence, the choice between solar energy systems against a conventional one must be cost effective on a long term basis (based on economic evaluation).

Since the availability of solar energy is intermittent and unpredictable it is rarely cost effective to have energy demands from solar energy alone. A solar system able to meet all the energy demands under the worst operating conditions for a long period would be greatly oversized.

The most economical way is to have

1. The solar system meets the basic energy demand while operating at its full capacity.
2. Let an auxiliary or backup system carry the peak load and unusual load.

The right proportion of solar versus auxiliary energy supply is to be determined by economics.



Schematic representation of a typical space heating system with air collectors is given in Figure. Dampers is indicated for the solar rock-bed charging mode. The main components of the building heating systems are as follows:

1. Air handling unit: a fan and two motor-driven dampers.
2. Heat storage unit (rock bed)
3. Temperature control system
4. Solar collectors

Depending on the position of dampers A and B, three modes of system operation can be achieved.

1. Dampers A and B open: This is the normal day time solar heating mode. The storage unit is bypassed. If the temperature sensor in the top of the collector array is below a necessary limit required for space heating, the auxiliary furnace is automatically turned on.
2. Damper A open and damper B closed: This mode is used whenever solar heat is collected but no space heating is required at the same time. The fan blows the solar heated air through the rock bed for thermal storage.
3. Damper A closed and damper B open: This mode is used during cloudy periods or during the night hours. The return air from the building is now pulled through the rock bed, where it picks up solar heat. The auxiliary furnace is activated automatically if the temperature is insufficient to meet the demand.

SOLAR WATER HEATING SYSTEMS

Most solar water heating systems have two main parts: a solar collector and a storage tank. The most common collector is called a flat plate collector. It consists of a thin, flat, rectangular box with a transparent cover that faces the sun mounted on the roof of building or home. Small tubes run through the box and carry the fluid – either water or other fluid, such as an antifreeze solution – to be heated. The tubes are attached to an absorber plate, which is painted with special coatings to absorb the heat. The heat builds up in the collector, which is passed to the fluid passing through the tubes.

An insulated storage tank holds the hot water. It is similar to water heater, but larger in size. In the case of systems that use fluids, heat is passed from hot fluid to the water stored in the tank through a coil of tubes. Solar water heating systems can be either active or passive systems.

1. The active systems, which are most common, rely on pumps to move the liquid between the collector and the storage tank.
2. The passive systems rely on gravity and the tendency for water to naturally circulate as it is heated.

1 Active Solar Water Heating Systems

The active water systems that can be used to heat domestic hot water are the same as the ones that provide space heat. A space heat application will require a larger system and additional connecting hardware to a space heat distribution system.

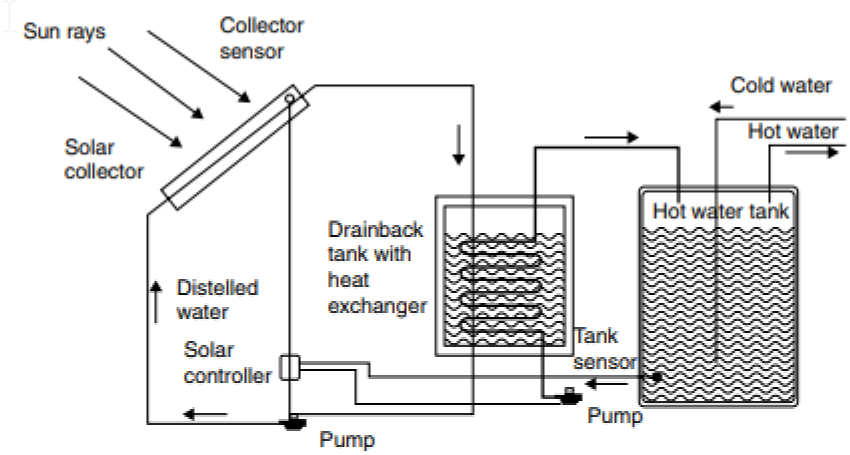
1.1 Parts of Water Heating Systems

There are five major components in active solar water heating systems:

1. Collector(s) to capture solar energy.
2. Circulation system to move a fluid between the collectors to a storage tank
3. Storage tank
4. Backup heating system
5. Control system to regulate the overall system operation

A typical active water heating system that exhibits effectiveness, reliability, and low maintenance is shown in Figure.

It uses distilled water as the collector circulating fluid. The collectors in this system will only have water in them when the pump is operating. This means that in the case of power failure as well as each night, there will be no fluid in the collector that could possibly freeze or cool down and delay the start-up of the system when the sun is shining. This system is very reliable and widely used. It requires that the collectors are mounted higher than the drain back tank or heat exchanger. This may be impossible to do in a situation where the collectors must be mounted on the ground. The fluids that are circulated into the collectors are separated from the heated water that will be used in the home by a double-walled heat exchanger. A heat exchanger is used to transfer the heat from the fluids circulating through the collectors to the water used in the home. The fluids that are used in the collectors can be water, oil, an antifreeze solution, or refrigerant. The heat exchangers should be double-walled to prevent contamination of the household water. The controller in these systems will activate the pumps to the collectors and heat exchanger when design temperature differences are reached. The heat exchanger may be separated from the storage tank or built into it. The systems that use antifreeze fluids need regular inspection (at least every 2 years) of the antifreeze solution to verify its viability. Oil or refrigerant circulating fluids are sealed into the system and will not require maintenance. A refrigerant system is generally more costly and must be handled with care to prevent leaking any refrigerant. This hot water system can be used for heating swimming pools and spas. Lower cost unglazed (no glass cover) collectors are available for this purpose.

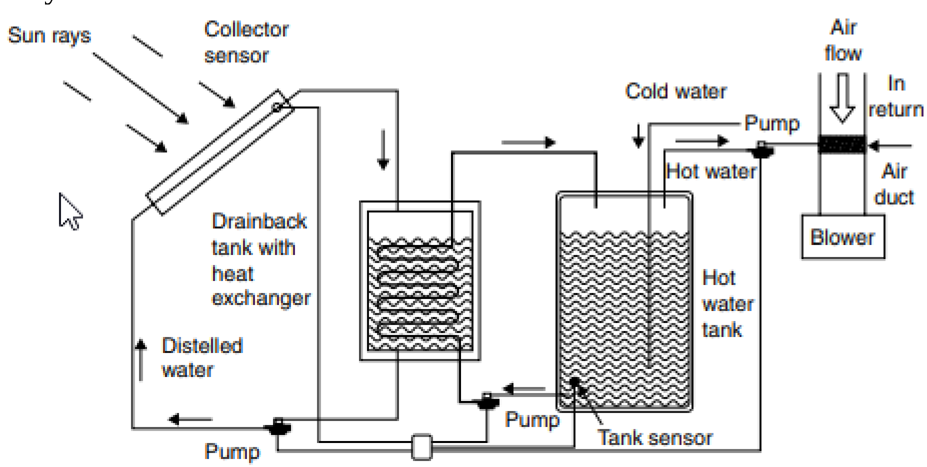


2 Active Solar Space Heating

The active solar space heating system can use the same operational components as the domestic water heating systems as shown in Figure 3.18, but ties into a heating distribution system that can use heated fluids as a heat source.

The distribution system includes hydronic radiator, floor coil systems, and forced air systems.

The fluid that is heated and stored (typically water) and can be distributed into the house heating system in the following ways:



1. Air distribution system: The heated water in the storage tank is pumped into a coil located in the return air duct whenever the thermostat calls for heat. The controller for the solar system will allow the pumping to occur if the temperature in the solar heated water is above a minimum amount needed to make a positive contribution to heating the home. An auxiliary heater can be used in two ways. It can add heat to the solar storage tank to maintain a minimum operating temperature in the storage tank at all times. In this case, the coil from the solar system will be located at the air handler supply plenum rather

than in the return air duct. The auxiliary heater can also be a conventional furnace that will operate less often due to the warm air entering the air handler from the solar coil in the return duct.

2. Hydronic system with radiators: The heated water is circulated in series with a boiler into radiators located in the living spaces. Modern baseboard radiators operate effectively at 140°C. Solar heating systems can very often reach that temperature. Using the solar system's heated water as the source of water for the boiler will reduce the boiler's energy use, particularly if it senses the incoming temperature and will not operate when that temperature is above the required distribution temperature.

3. Hydronic system with in-slab heat: The solar heated water is pumped through distribution piping located in the floor of the home. Lower temperatures are used in this type of system (the slab is not heated above 80° in most cases). The auxiliary heat can be connected in series with the solar system's heated output water or it can be connected to the solar tank to provide a minimum temperature.

The space heating system, like the domestic water heating system, must be backed up by an auxiliary heating system. It is not practical to size a solar system to provide a home's entire heat requirement under the worst conditions. The system would become too large, too costly, and oversized for most of the time. The storage system should be sized to approximately 1.5 gallons of storage for each square foot of collector area.

PASSIVE SOLAR WATER HEATING SYSTEMS

A passive solar water heating system uses natural convection or household water pressure to circulate water through a solar collector to a storage tank or to the point of use. Active systems employ pumps and controllers to regulate and circulate water. Although passive system is generally less efficient than active systems, the passive approach is simple and economical.

Passive water heating systems must follow the same parameters for installations as that of active systems – south facing non-shaded location with the collector tilted at the angle of our latitude. Since the storage tank and collector are combined or in very close proximity, roof structural capacities must accommodate the extra weight of a passive system.

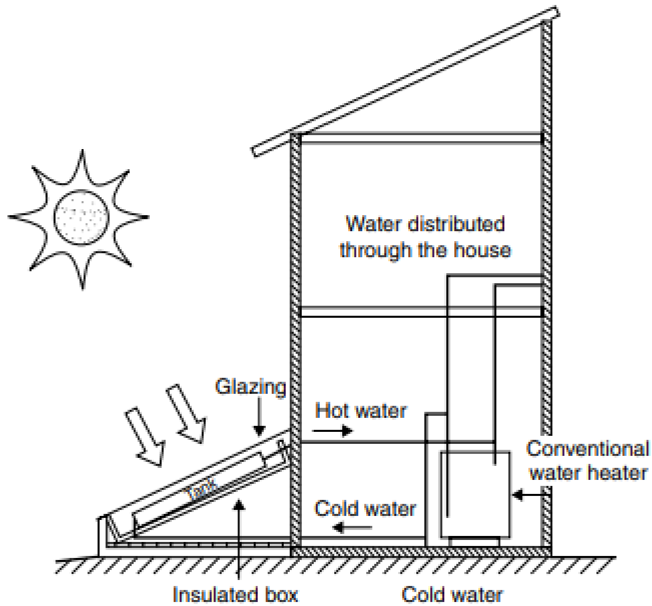
1 Types of Passive Water Heaters

Two types of passive water heaters are batch and thermosiphon systems.

1.1 Batch System

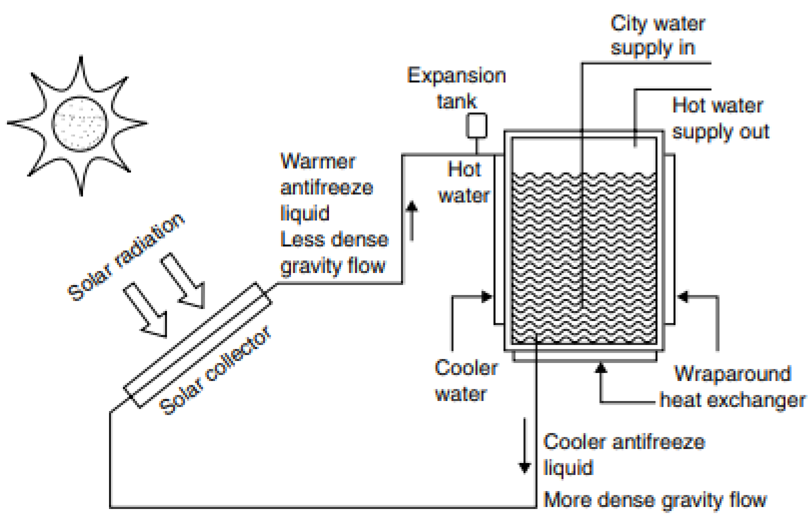
The batch system is the simplest of all solar water heating systems, as depicted in Figure 3.19. It consists of one or more metal water tanks painted with a heat absorbing black coating and placed in an insulating box or container with a glass or plastic cover that admits sunlight to strike the tank directly. The batch system's storage tank is the collector as well. These systems will use the existing house pressure to move water through the system. Each time a hot water tap is opened, heated water from the batch system tank is removed and replaced by incoming cold water. The piping that connects to and from the batch heater needs to be highly insulated. On a cold night, when no one is drawing hot water, the water in the pipes is standing still and vulnerable to freezing. In many applications, insulated polybutylene piping is used because the pipe can expand if frozen. The water in the batch heater itself will not freeze because there is adequate mass to keep it from freezing.

Since the tank that is storing the heated water is sitting outside, there will be heat loss from the tank during the night. This can be minimized by an insulating cover placed on the heater in the evening. The most effective use of a batch water heater is to use hot water predominantly in the afternoon and evenings when the temperature in the tank will be the highest.



1.2 Thermosiphon Systems

The thermosiphon system uses a flat plate collector and a separate storage tank that must be located higher than the collector as shown in Figure 3.20. The collector is similar to those used in active systems.



The storage tank located above the collector receives heated water coming from the top of the collector into the top of the storage tank. Colder water from the bottom of the storage tank will be drawn into the lower entry of the solar collector to replace the heated water that was thermosiphoned upward. The storage tank may or may not use a heat exchanger. The thermosiphon system is more costly and complex than the batch system. In our area, it is best to use an indirect system (one that employs a heat exchanger). In that case, antifreeze can be used in the system eliminating freeze ups.

APPLICATIONS OF SOLAR WATER HEATING SYSTEMS

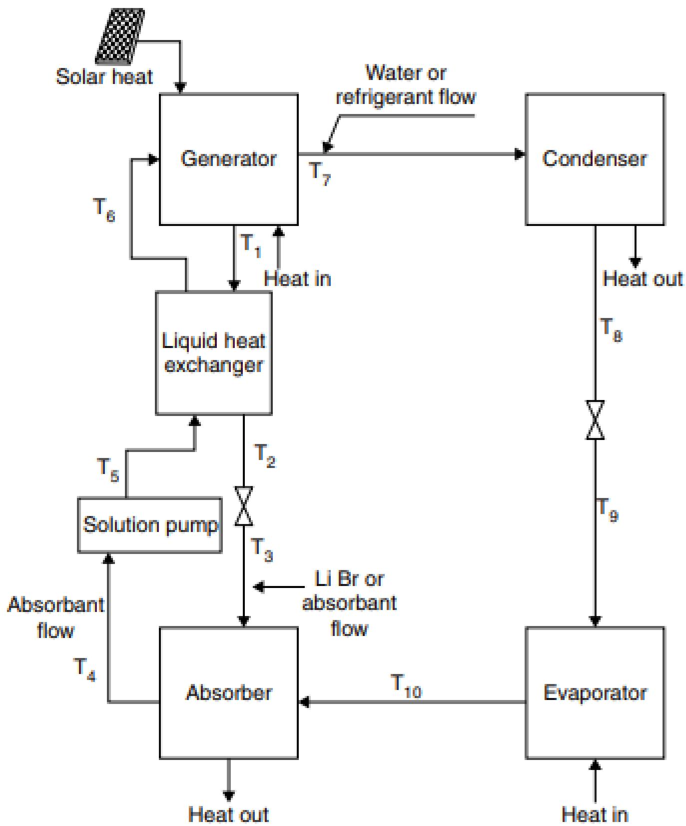
The following are a few industrial applications of solar water heaters.

1. Hotels: bathing, kitchen, washing, laundry applications
2. Dairies: ghee (clarified butter) production, cleaning and sterilizing, pasteurization
3. Textiles: bleaching, boiling, printing, dyeing, curing, ageing, and finishing

4. Breweries and distilleries: bottle washing, work preparation, boiler feed heating
5. Chemical/bulk drugs units: fermentation of mixes, boiler feed applications
6. Electroplating or galvanizing units: heating of plating baths, cleaning, degreasing applications
7. Pulp and paper industries: boiler feed applications, soaking of pulp

ACTIVE SOLAR SPACE COOLING

Solar space cooling is quite costly to implement. The cooling process progresses as follows:
The absorber holds an absorbent-refrigerant mixture that is delivered to the generator through a liquid pump.
The generator takes the absorbent-refrigerant mixture and heats it up using the external solar energy that has been collected through a source such as a solar panel. The solution starts to boil in reaction to the heat, turning water into vapor which flows to the condenser.
The condenser liquefies the water vapor, rejecting heat in the process which is collected by the heat sink. The new liquid condensate is then directed towards the evaporator through an expansion valve.
Finally, evaporation of the refrigerant at low pressure causes the evaporator to absorb the heat from the cooled space, creating the cooling effect.
At the end, the vaporized refrigerant returns to the absorber and the cycle repeats. Solar power is responsible for driving this cycle.



SOLAR AIR HEATING

Solar-heated air can be used for drying most crops that require warm air. Solar heated air is ideal for drying delicate foods since it will not burn or risk potential damage from high temperature steam heat. Solar heat is non-polluting and best of all, it incurs no fuel costs.
Existing commercial drying operations can be converted to utilize solar heat by installing our system to remove heat from the building's metal roof or wall. We remove heat from under the metal panels, add

the duct, and connect the ducts to the intake of the drier fans. The system then removes the heated air from the underside of the panels and passes the air to the drying chamber.

Simple sensors are installed in the air flow and use thermostatic controls to turn off the incoming air flow when the temperature is not high enough for solar heating. The existing system then operates, as it always has, burning high-cost fuel but serving the drying process.

For some in-field applications, one can use a ground-mounted polymer system that is low cost and very transportable. In new building, metal roofs and walls are integrated with the building’s structure. By trapping air into a confined space which has sunlight hitting it, the trapped air is heated up naturally by the solar power of the sun. This type of natural heat transfer is also used for solar water heating. The hot air rises, and this is a key component to solar heating with convection.

Inside houses, the coldest air is closest to the floor and the warmest is up high along the ceiling. As the warm air at the top of the room cools, it drops lower, and as the cooler air is warmed up, it rises.In order to use this process naturally in houses and particularly to make use of the warming power of solar energy, means has to be found or create a way to have the cool air go into a space that is warmed up by the sun. That same space usually allows the warm air to escape once it has reached a certain point.

In many cases, all you need is some sort of confined area to direct and control airflow. For example, if you have a sunny window, you could put a piece of black fabric, wood, plastic, or metal against that window frame to trap the air in for a short period of time. There needs to be a space between the black material you choose to use, and the glass window pane itself. Usually, this space is at least a few inches, but there can be space as much as 5–6 inches between your window glass and the black material.

It is a solar thermal technology in which the energy from the sun, solar insolation, is captured by an absorbing medium and used to heat air. Solar air heating is a renewable energy heating technology used to heat or condition air for buildings or process heat applications. It is typically the most cost effective out of all the solar technologies, especially in commercial and industrial applications, and it addresses the largest usage of building energy in heating climates, which is space heating and industrial process heating.

Solar air collectors can be commonly divided into two categories:

1. Unglazed air collectors or transpired solar collector (used primarily to heat ambient air in commercial, industrial, agricultural and process applications).
2. Glazed solar collectors (recirculation types that are usually used for space heating).

SOLAR DRYERS

Solar dryers can be utilized for various domestic purposes. They also find numerous applications in industries such as textiles, wood, fruit and food processing, paper, pharmaceutical, and agro-industries.

3.13.1 Advantages

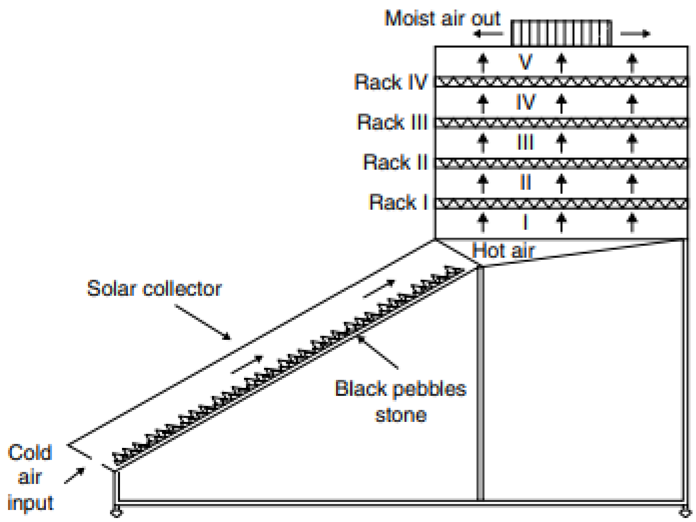
Solar dryers are more economical when compared to dryers that run on conventional fuel or electricity. The drying process is completed in the most hygienic and eco-friendly way. Solar drying systems have low operation and maintenance costs.

Solar dryers last longer. A typical dryer can last 15–20 years with minimum maintenance.

3.13.2 Limitations

1. Drying can be performed only during sunny days, unless the system is integrated with a conventional energy-based system.
2. Due to limitations of solar energy collection, the solar drying process is slow in comparison with dryers that use conventional fuels.
3. Normally, solar dryers can be utilized only for drying at 40°C–50°C.

One well-known type of solar dryer is shown in Figure



It was designed for the particular requirements of rice but the principles hold for other products and design types, since the basic need to remove water is the same. Air is drawn through the dryer by natural convection. It is heated as it passes through the collector and then partially cooled as it picks up moisture from the rice. The rice is heated both by the air and directly by the sun. Warm air can hold more moisture than cold air so the amount required depends on the temperature to which it is heated in the collector as well as the amount held (absolute humidity) when it entered the collector.

CROP DRYING

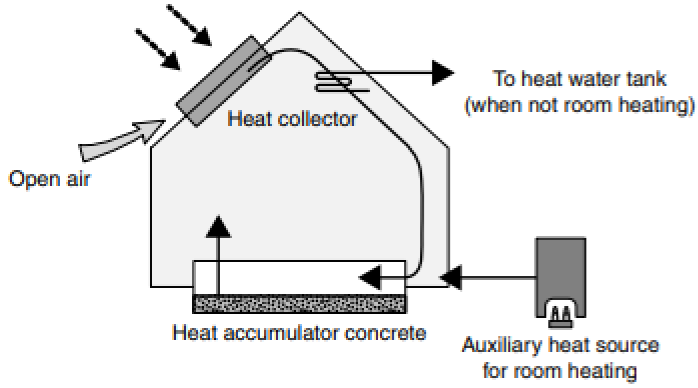
Controlled drying is required for various crops and products, such as grain, coffee, tobacco, fruits, vegetables, and fish. Their quality can be enhanced if the drying is properly carried out. Solar thermal technology can be used to assist with the drying of such products. The main principle of operation is to raise the heat of the product, which is usually held within a compartment or box; while, at the same time, passing air through the compartment to remove moisture. The flow of air is often promoted using the ‘stack’ effect that takes advantage of the fact that hot air raises, and therefore, it can be drawn upwards through a chimney, while drawing in cooler air from below. Alternatively, a fan can be used. The size and shape of the compartment varies depending on the product and the scale of the drying system. Large systems can use large barns, while smaller systems may have a few trays in a small wooden housing.Solar crop drying technologies can help reduce environmental degradation caused by the use of fuel wood or fossil fuels for crop drying and can also help to reduce the costs associated with these fuels and hence the cost of the product. Improving and protecting crops also have beneficial effects on health and nutrition.

SPACE COOLING

The majority of the developing countries lies within the tropics and have little need of space heating. However, there is a demand for space cooling. The majority of the world warm climate cultures have again developed traditional, simple, elegant techniques for cooling their dwellings, often using effects promoted by passive solar phenomenon.

There are many methods for minimizing the heat gain. These include situating a building in shade or near water, using vegetation or landscaping to direct wind into the building, good town planning to optimize the prevailing wind and available shade. Buildings can be designed for a given climate; domed roofs and thermally massive structures in hot arid climates, shuttered and shaded windows to prevent heat gain, open structure bamboo housing in warm and humid areas. In some countries, dwellings are constructed underground and take advantage of the relatively low and stable temperature of the surrounding ground. There are as many options, as there are people.

Solar heating by convection is a natural process that involves trapping air and letting it warmup before releasing it back into a given space. Convection heating is often used as a solar heating source because the two naturally go hand in hand (see Fig.).



Type 1 is a very simple construction: ambient air passes from a glazed or unglazed collector directly into the room to provide ventilation and heating. Applications include vacation cottages (dehumidification) and large industrial buildings requiring adequate ventilation.

Type 2 circulates room air to the collector. The heated air rises to a thermal storage ceiling from which it is conveyed back into the room. This system uses natural convection and is well suited for apartment buildings.

Type 3 is particularly suited for retrofitting poorly insulated buildings. Collector heated air passes through a cavity between an outer insulated wall and an inner facade. This creates a buffer that considerably reduces heat loss via the facade of the building.

Type 4 is the classical solar air heating system and is commonly used. Collector heated air is circulated through channels in the floor or in the wall. Heat is radiated into the room with a time delay of 4 to 6 h. The advantage of this system consists in the large radiating surfaces, which provide for a comfortable climate. Systems with forced ventilation (fans) provide the best efficiency and thermal output. They may be used in buildings with large surfaces, which serve as radiation sources.

Type 5 is an advanced version of type 4; room air is circulated through separate channels of the storage. Thus, heat can be stored for a long period of time and released when it is needed.

However, this type is rarely used as investment costs are rather high

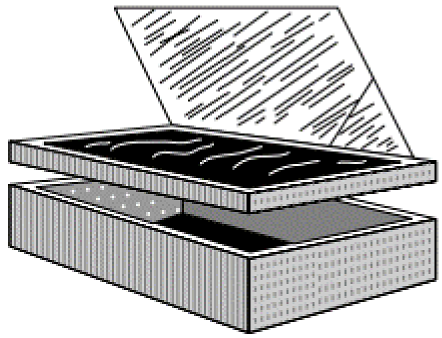
SOLAR COOKERS

Solar cooking is a technology that has been given a lot of attention in recent years in developing countries. The basic design is that of a box with a glass cover. The box is lined with insulation and a reflective surface is applied to concentrate the heat onto the pots. The pots can be painted black to help with the heat absorption. The solar radiation raises the temperature sufficiently to boil the contents in the pots. Cooking time is often considerably slower than conventional cooking stoves, but there is no fuel cost.

People use solar cookers primarily to cook food and pasteurize water, although additional uses are continually being developed. Numerous factors including access to materials, availability of traditional cooking fuels, climate, food preferences, cultural factors, and technical capabilities affect people’s approach to solar cooking.

Many types of cookers exist. Simple solar cookers use the following basic principles:

1. Concentrating sunlight: A reflective mirror of polished glass, metal, or metalized film is used to concentrate light and heat from the sun into a small cooking area, making the energy more concentrated and increasing its heating power

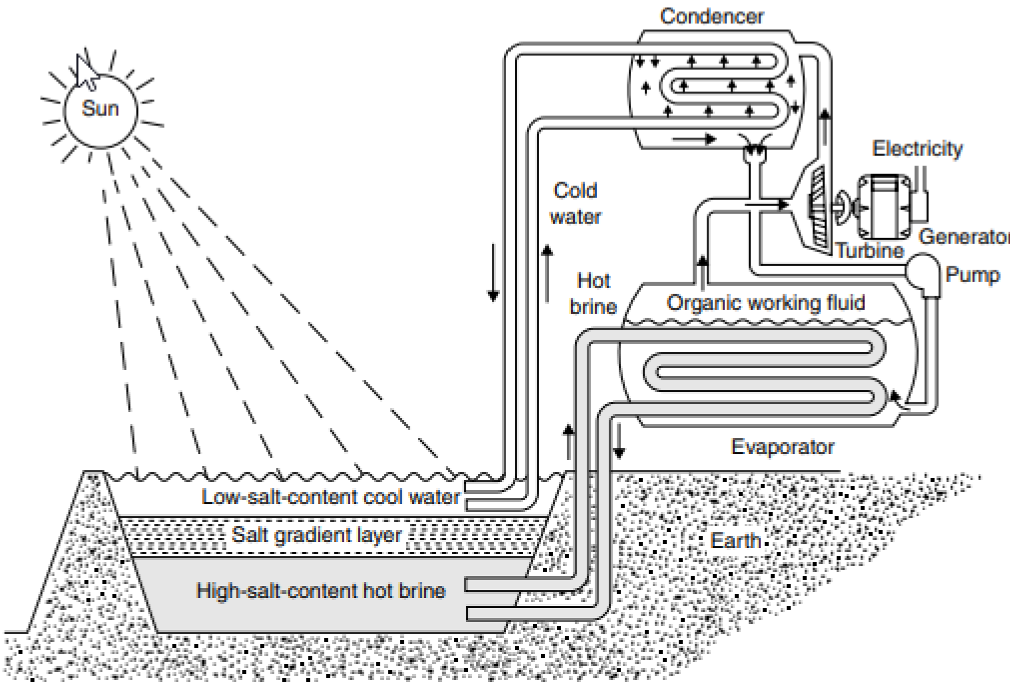


2. Converting light to heat: A black or low reflectivity surface on a food container or the inside of a solar cooker will improve the effectiveness of turning light into heat. Light absorption converts the sun's visible light into heat, substantially improving the effectiveness of the cooker.
3. Trapping heat: It is important to reduce convection by isolating the air inside the cooker from the air outside the cooker. A plastic bag or tightly sealed glass cover will trap the hot air inside. This makes it possible to reach similar temperatures on cold and windy days as on hot days.
4. Greenhouse effect: Glass transmits visible light but blocks infrared thermal radiation from escaping. This amplifies the heat trapping effect.
With an understanding of basic principles of solar energy and access to simple materials such as cardboard, aluminium foil, and glass, one can build an effective solar cooking device. The basic principles of solar box cooker design and identification of a broad range of potentially useful construction materials are continuously developed. These principles are presented in general terms so that they are applicable to a wide variety of design problems. Whether the need is to cook food, pasteurize water, or dry fish or grain, the basic principles of solar, heat transfer, and materials apply. The application of a wide variety of materials and techniques as people make direct use of the sun's energy is continuously under development.

SOLAR POND

One of the best ways of harnessing solar energy is through solar ponds. It is basically a pool of water that collects and also stores solar energy. The peculiarity of the solar pond is that it has layers of salt solutions of differing concentrations, and thus, different densities to a certain depth. Once this depth is reached, then water with uniform, high salt concentration is obtained. The solar pond is a relatively low technology and low cost approach for harvesting solar energy. Todevelop a solar pond, pond is filled with three layers of water as shown in Figure.
1. The top layer is cold and has relatively little salt content.
2. Next is the intermediate insulating layer that has a salt gradient that maintains a density gradient. It is this density gradient that helps in preventing heat exchange with the natural convection of water.
3. The bottom layer is hot up to 100°C and has a high salt content.
It is because of these different salt contents in the different layers of water that the different layers have different densities. With the different densities in the water, the development of convection currents is prevented, which would have transferred heat to the surface of the pond, and then to the air above. Without these convection currents, heat is trapped in the salty bottom layer of the solar pond, which is used for heating of buildings, industrial processes, generation of electricity, and other purposes. In

addition to the abovementioned uses, solar ponds can also be used in water desalination and for storage of thermal energy.
In this system, a large salty lake is used as a plate collector. With the right salt concentration in the water, the solar energy can be absorbed at the bottom of the lake. The heat is insulated by different densities of the water, and at the bottom, the heat **can reach 90°C,** which is high enough to run a vapour cycle engine; at the top of the pond, the temperature can reach 30°C. There are three different layers of water in a solar pond: the top layer has less concentration of salt, the intermediate layer acts as a thermal insulator, and finally, the bottom layer has a high concentration of salt. These systems have a low solar to electricity conversion efficiency, less than 15% (having an ambient temperature of 20°C and storage heat of 80°C). One advantage of this system is that because the heat is stored, it can run day and night if required. Further, due to its simplicity, it can be constructed in rural areas in developing countries.

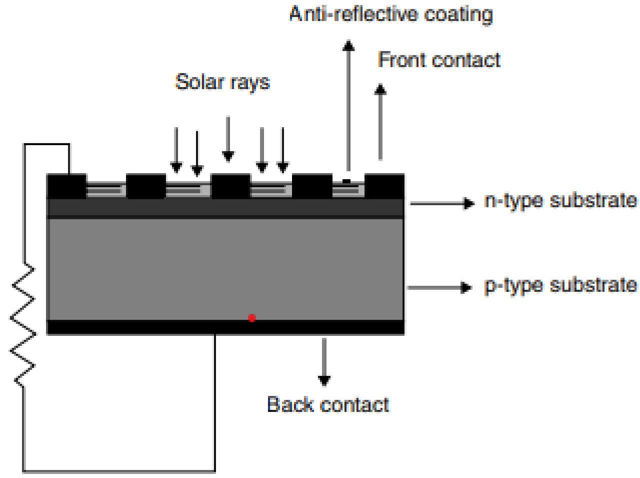


Solar Cells: A solar cell or photovoltaic cell is an electrical device that converts the energy of light directly into electricity by photovoltaic effect. They are made of special materials that are semiconductors. These semiconductors produce electricity when sun light falls onto its surface. It is 5 to 11 times more expensive to produce electricity from the sun than it is from fossil and nuclear fuels. The first problem is with the cost of the solar cell technology that uses expensive semiconductor materials to convert sunlight directly into DC electricity. Moreover, the solar cell efficiency is not very encouraging yet. Practical efficiency of solar cells lies somewhere in between 10% and 25%. Reduction of solar cell material costs and increasing the practical efficiency of solar cells are lively topics of current research that will necessitate huge investment and time-consuming R&D activities.

Components of Solar Cell System
These include solar cell panels, one or more batteries, a charge regulator or controller for a standalone system, an inverter for a utility grid-connected system, requirement of alternating current (AC) rather than direct current (DC), wiring, and mounting hardware or a framework.

Elements of Silicon Solar Cell

The basic elements of a solar cell is described in Figure.



The following are the basic elements:

1. Substrate: It is an unpolished p-type wafer referred to as p-region base material. The important parameters to be kept in mind while choosing a wafer for solar cells are its orientation, resistivity, thickness, and doping. Typical thickness of wafers used for solar cells is 180–300 µm.

The typical resistivity values are in 1–2 Ω cm. The doping should be close to 5 × 1015/cm3 to 1 × 1016/cm3. The wafer can be single crystalline or multi-crystalline.

2. Emitter: The emitter formation involves the doping of silicon with pentavalent impurities such as phosphorus, arsenic, and antimony. However, for solar cell applications, phosphorus is the widely used impurity. The doping is done by the process of diffusion. The basic idea is to introduce the wafer in an environment rich in phosphorus at high temperatures. The phosphorus diffuses in, due to the concentration gradient, and it can be controlled by varying the time and temperature of the process. Commonly used diffusion technique makes use of POCl3 as the phosphorus source. The process is done at temperatures of 850°C to 1,000°C. The typical doping concentration will be of the order of 1×1019/cm3. The junction depths are in the range of 0.2–1 µm. This is also commonly known as n-region diffused layers

3. Electrical contacts: These are essential to a photovoltaic cell since they bridge the connection between the semiconductor material and the external electrical load. It includes

(a) Back contact: It is a metallic conductor completely covering back. The back contact of a cell is located on the side away from the incoming sunlight and is relatively simple. It usually consists of a layer of aluminium or molybdenum metal.

(b) Front contact: Current collection grid of metallic finger type is arranged in such a way that photon energy falls on n-region diffused layers. The front contact is located on the side facing the light source and is more complicated. When light falls on the solar cell, a current of electrons flow over the surface. If contacts are attached at the edges of the cell, it will not work well due to the great electrical resistance of the top semiconductor layer; only a small number of electrons will make it to the contact. To collect the maximum current, the contacts must be placed across the entire surface of a solar cell.

This is done with a grid of metal stripes or fingers. However, placing a large grid, which is opaque, on the top of the cell shades active parts of the cell from the light source; as a result, this significantly reduces the conversion efficiency. To improve the conversion efficiency, the shading effect must be minimized.

(c) Anti-reflective coatings: Anti-reflective coatings are applied to reduce surface reflec tion and maximize cell efficiency in solar glass and silicon solar cell manufacturing.

It helps to reduce the reflection of desirable wavelengths from the cell, allowing more light to reach the semiconductor film layer, increasing solar cell efficiency. When a thin-film nano-coating of anti-reflection coating of silicon dioxide (SiO_2) and titanium dioxide (TiO_2) is applied, there seems to be an increase in cell efficiencies by 3–4%

Solar Cell materials

Many combinations of materials and methods of fabrication of photovoltaic cells are now either in practical use or in various developmental stage. However, silicon is the most widely used basic material because of its suitability and its availability in abundance. More than 80% of solar cells currently produced are crystalline silicon solar cells. Nearly all of the other 20% are developed as amorphous silicon solar cells. Silicon wafers have long been the primary base for assembly.

The absorption coefficient of a material indicates how far light with a specific wavelength (or energy) can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material. Again, the absorption coefficient of a solar cell depends on two factors: the material making up the cell, and the wavelength or energy of the light being absorbed.

The bandgap of a semiconductor material is the minimum energy needed to move an electron from its bound state within an atom to a free state. This free state is where the electron can be involved in conduction. The lower energy level of a semiconductor is called the ‘valence band.’ The higher energy level where an electron is free to roam is called the ‘conduction band.’ The bandgap (often symbolized by Eg) is the energy difference between the conduction band and the valence band.

Solar cell material has an abrupt edge in its absorption coefficient, because light with energy lesser than the material’s bandgap cannot free an electron, it is not absorbed. A solar cell consists of semiconductor materials.

1 **Silicon**

This remains the most popular material for solar cells, including these types:

1. Monocrystalline or single crystal silicon
2. Multi-crystalline silicon
3. Polycrystalline silicon
4. Amorphous silicon

Polycrystalline wafers are made by a casting process in which molten silicon is poured into a mould and allowed to set. Then, it is sliced into wafers. As polycrystalline wafers are made by casting, they are significantly cheaper to produce, but not as efficient as monocrystalline cells. The lower efficiency is due to imperfections in the crystal structure resulting from the casting process.

Amorphous silicon, one of the thin-film technologies, is made by depositing silicon onto a glass substrate from a reactive gas like silane (SiH_4). This type of solar cell can be applied as a film to low cost substrates such as glass or plastic. Other thin-film technologies include thin multi-crystalline silicon, copper indium diselenide or cadmium sulphide cells, cadmium telluride or cadmium sulphide cells and gallium arsenide cells. There are many advantages of thinfilm cells including easier deposition and assembly, the ability to be deposited on inexpensive substrates or building materials, the ease of mass production, and the high suitability to large applications.

Other types of PV materials that show commercial potential include copper indium diselenide ($CuInSe_2$), cadmium telluride (CdTe), and amorphous silicon as the basic material.

2 **Thin Film**

Thin-film solar cells use layers of semiconductor materials only a few micrometres thick. Thin film technology has made it possible for solar cells to now double as these materials:

1. Rooftop or solar shingles

2. Roof tiles
3. Building facades
4. Glazing for skylights or atria

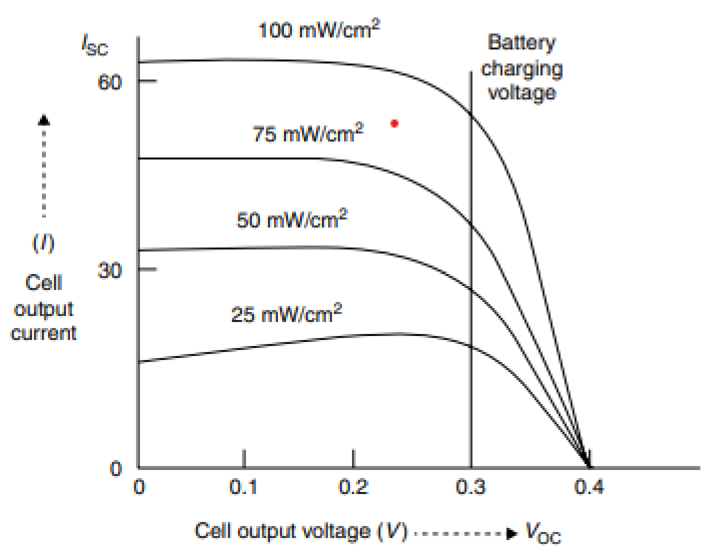
Thin-film photovoltaic cells made of CuInSe or CdTe that are being increasingly employed along with amorphous silicon. The recently discovered cells based on mesoscopic inorganic or organic semiconductors commonly referred to as ‘bulk’ junctions due to their three-dimensional structure. These junctions are very attractive alternatives that offer the prospect of very low cost fabrication. The prototype of this family of devices is the dye-sensitized solar cell (DSC), which accomplishes the optical absorption and the charge separation processes by the association of a sensitizer as light-absorbing material with a wide bandgap semiconductor of mesoporous or nano-crystalline morphology. Further, research is booming in the area of third generation photovoltaic cells where multi-junction devices and a recent breakthrough concerning multiple carrier generation in quantum-dot absorbers offer promising perspectives.

Practical Solar Cells

Solar cells are now manufactured from a number of different semiconductors that are summarized in the following points. In addition, there is considerable activity to commercially manufacture the dye-sensitized solar cells.

1. Crystalline silicon cells: They dominate the photovoltaic market. To reduce the cost, these cells are now often made from multi-crystalline material, rather than from the more expensive single crystals. Crystalline silicon cell technology is well established. The modules have long lifetime (20 years or more) and their best production efficiency is approaching 18%.
2. Amorphous silicon solar cells: They are cheaper (but also less efficient) type of silicon cells made in the form of amorphous thin films that are used to power a variety of consumer products; however, larger amorphous silicon solar modules are also becoming available.
3. Cadmium telluride and copper indium diselenide: Thin-film modules are now beginning to appear on the market and hold the promise of combining low cost with acceptable conversion efficiencies.
4. High-efficiency solar cells: From gallium arsenide, indium phosphide, or their derivatives
are used in specialized applications, for example, to power satellites or in systems that operate under high-intensity concentrated sunlight

I – V Characteristics of Solar Cells



The voltage output of the cell (V), in general, can be obtained as

V = (kT/e) loge [1+ (IS – I)/I0] ----------------------(1)

Equation (1) represents the I–V characteristic of solar cell and it is shown in Figure under different illumination levels.

On an I–V characteristic, the vertical axis refers to the current (I) and the horizontal axis refers to voltage (V). The actual I–V curve typically passes through two significant points:

1. The short-circuit current (ISC) is the current produced when the positive and negative terminals of the cell are short-circuited and the voltage between the terminals is zero, which corresponds to a load resistance of zero.
2. The open-circuit voltage (VOC) is the voltage across the positive and negative terminals under open-circuit conditions when the current is zero, which corresponds to a load resistance of infinity.

The cell may be operated over a range of voltages and currents.

Efficiency of Solar Cells

Energy conversion efficiency (h) is defined as the ratio of power output of cell (in watts) at its maximum power point (PMAX) and the product of input light power (E, in W/m2) and the surface area of the solar cell (S in m2) under standard conditions

h = maximum output power/(irradiance × area) = PMAX/(E × S) -------------------(1)

The performance of a photovoltaic device defines the prediction of the power that the cell will produce. Current–voltage (I–V) relationships, which measure the electrical characteristics of solar cell devices, are represented by I–V curves. These I–V curves are obtained by exposing the cell to a constant level of light while maintaining a constant cell temperature, varying the resistance of the load, and measuring the current that is produced.

By varying the load resistance from zero (a short circuit) to infinity (an open circuit), researchers can determine the highest efficiency as the point at which the cell delivers maximum power.

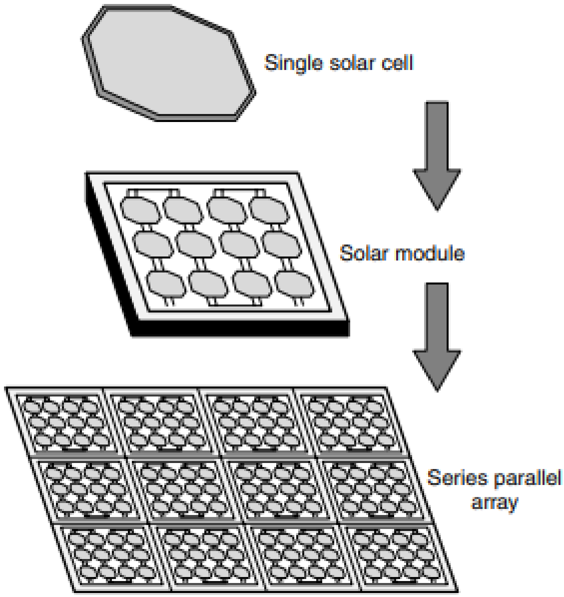
The power is the product of voltage and current. Therefore, on the I–V curve, the maximum power point (PMAX) occurs where the product of current and voltage is a maximum. No power is produced at the short-circuit current with no voltage or at open-circuit voltage with no current. Therefore, the maximum power generated is expected to be somewhere between these two points. Maximum power is generated at only one place on the power curve, at about the ‘knee’ of the curve. This point represents the maximum efficiency of the solar device at converting sunlight into electricity.

Photovoltaic panels (series and parallel arrays)

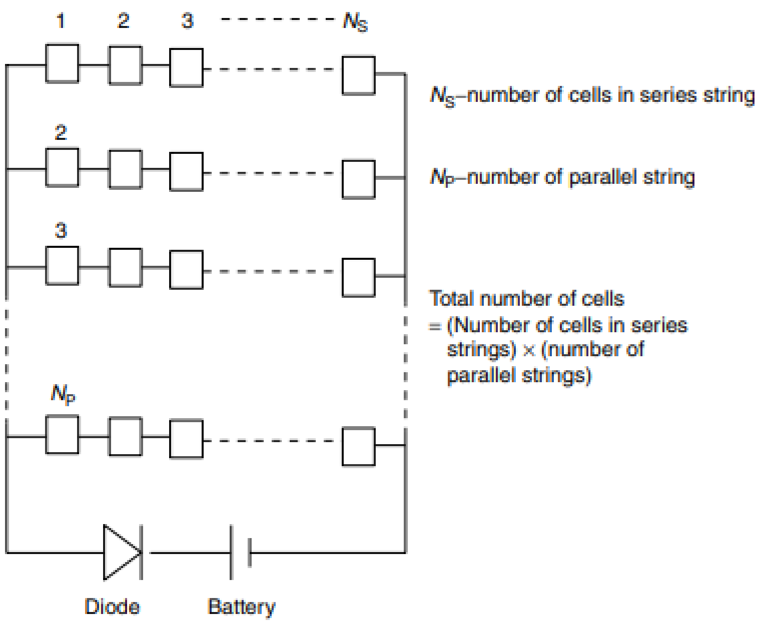
As single solar cell has a working voltage and current of about 0.5 V and 50 mA, respectively, they are usually connected together in series (positive to negative) to provide larger voltages. Parallel connection of several strings of cells will give rise to higher current output when compared with single series string of cells.

Photovoltaic panels (as shown in Fig.) are made in a wide range of sizes for different purposes. They generally fall into one of three basic categories:

Low voltage or low power panels are made by connecting between 3 and 12 small segments of amorphous silicon photovoltaic with a total area of a few square centimetres for voltages between 1.5 and 6 V and outputs of a few milliwatts. Although each of these panels is very small, the total production is large. They are used mainly in watches, clocks and calculators, cameras, and devices for sensing light and dark, such as night lights.



Small panels of 1–10 W and 3–12 V, with areas from 100 cm2 to 1,000 cm2 are made by either cutting 100 cm2 single or polycrystalline cells into pieces and joining them in series, or by using amorphous silicon panels. The main uses are for radios, toys, small pumps, electric fences, and trickle charging of batteries.



Large panels, ranging from 10 to 60 W, and generally either 6 or 12 V, with areas of 1,000 cm2 to 5,000 cm2 are usually made by connecting from 10 to 36 full-sized cells in series. They are used either separately for small pumps and caravan power (lights and refrigeration) or in arrays to provide power for houses, communications, pumping, and remote area power supplies (RAPS).

If the load resistance is very low, the cell acts as if it is shortened at the output of light falling on it. If the load resistance is very high, the cell acts as if it is open-circuited and the voltage rises very rapidly to maximum voltage. The current at a voltage is limited by the amount of sunlight and load resistance. This characteristic is ideal for charging battery.

For charging, a 12 V battery by a 2 cm × 2 cm (0.3 V battery charging voltage), silicon cells required = 12/0.3 = 40 cells in series string.

A number of optimal solar array designs are available. However, the arrangement of series–parallel array has been most preferable, as it results in optimal performance characteristic under many conditions including shading, cell failure, non-uniform illumination, and unequal I–V characteristics.

A diode is placed in series with the positive terminal of battery as shown in Figure. This will prevent reverse current flow (a small battery drain) when the cells are not receiving sufficient light to chary battery