UNIT III - SOLAR PV AND THERMAL SYSTEMS

Solar Radiation, Radiation Measurement, Solar Thermal Power Plant, Central Receiver Power Plants, Solar Ponds - Thermal Energy storage system with PCM- Solar Photovoltaic systems: Basic Principle of SPV conversion – Types of PV Systems- Types of Solar Cells, Photovoltaic cell concepts: Cell, module, array, PV Module I-V Characteristics, Efficiency & Quality of the Cell, series and parallel connections, maximum power point tracking, Applications.

Introduction

The basic principle behind both solar panel – solar photovoltaic (PV) and solar thermal – is the same. They absorb raw energy from the sun and use it to create usable energy. In solar PV systems this is through the creation of electricity, whereas thermal systems are used directly for heating water or air. The amount of solar radiation on the earth surface can be instrumentally measured using Pyrheliometer, Pyranometer, Photoelectric sunshine recorder and many instruments. Solar thermal power plants collect and concentrate sunlight to produce the high temperature heat needed to generate electricity. Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. A photovoltaic module consists of multiple PV cells connected in series to provide a higher voltage output. A photovoltaic array is a system composed of multiple PV modules. They can be connected in one or more series circuits, which are connected to a combiner box to provide a single direct-current output.

Solar Radiation

Solar radiation, often called the solar resource, is a general term for the electromagnetic radiation emitted by the sun. The sun emits electromagnetic radiations as a black body having a surface temperature of about 6000 K. This is because of the nuclear reaction running in it, where the sun is converting hydrogen into helium. The radius of the sun amounts to 1.39×10^9 m. The total radiation power received from the sun on a unit area perpendicular to the sun rays at the mean earth sun distance, termed an astronomical unit, is called the solar constant (SC), where 1 astronomical unit = 1AU = 1.496×10^{11}m.

The solar radiation intensity at other distances is expressed in terms of SC with SC = 1.353 kW/m^2. Like a black body radiation, the sun's radiation covers a wide spectrum of wavelengths from deep ultraviolet to far infrared. The power spectral distribution of the sunlight is shown in Fig. 1. The vertical axis represents the spectral irradiance I(λ) while the horizontal axis represents the wavelength in mm. The irradiance I(λ) is equal to the incident solar power/m^2/δλ = [W/m^2/mm], where δλ is the respective wavelength range in μm. It is clear from this figure that the maximum spectral irradiance lies at λ = 0.5μm. The spectral irradiance decreases because of the presence of air in the atmosphere. The air molecules scatter and absorb the solar radiation. There are multiple absorption bands for O_2, H_2O, and CO_2. It is important to notice that the solar irradiance resembles the black body radiation at ~ 6000 K represented by the dashed line.

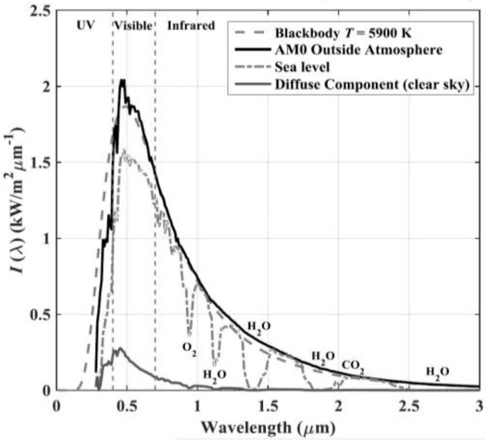


Fig.1. The power spectral distribution of the sunlight

The solar power intensity without the effect of the atmosphere or ground surface is called the Air Mass Zero where one AM0 = 1 SC = 135.3 mW/cm^2. The solar power intensity after crossing one air mass perpendicular to the earth is called the air mass 1, AM1. It represents the area under the spectral irradiance curve and amounts to 92.5 mW/cm^2. If θ is the angle of incidence with normal to the earth surface, then the optical path in units of the air mass will be larger. The air mass AM = 1/(cos θ).

As the solar radiation passes through the atmosphere, it gets absorbed, scattered, reflected, or transmitted. All these processes result in reduction of the energy flux density. Actually, the solar flux density is reduced by about 30% compared to extraterrestrial radiation flux on a sunny day and is reduced by as much as 90% on a cloudy day. The following main losses should be noted:

- ❖ absorbed by particles and molecules in the atmosphere - 10-30%
- ❖ reflected and scattered back to space - 2-11%
- ❖ scattered to earth (direct radiation becomes diffuse) - 5-26%

- As a result, the direct radiation reaching the earth surface (or a device installed on the earth surface) never exceeds 83% of the original extraterrestrial energy flux. This radiation that comes directly from the solar disk is defined as beam radiation.
- The scattered and reflected radiation that is sent to the earth surface from all directions (reflected from other bodies, molecules, particles, droplets, etc.) is defined as diffuse radiation. The sum of the beam and diffuse components is defined as total (or global) radiation. The beam radiation can be concentrated, while the diffuse radiation, in many cases, cannot be concentrated.
- Short-wave radiation, in the wavelength range from 0.3 to 3 μm, comes directly from the sun. It includes both beam and diffuse components.
- Long-wave radiation, with wavelength 3 μm or longer, originates from the sources at near-ambient temperatures - atmosphere, earth surface, light collectors, other bodies.
- The solar radiation reaching the earth is highly variable and depends on the state of the atmosphere at a specific locality. Two atmospheric processes can significantly affect the incident irradiation: scattering and absorption.

Scattering is caused by interaction of the radiation with molecules, water and dust particles in the air. The amount of light scattered depends on the number of particles in the atmosphere, particle size and the total air mass the radiation comes through.

Absorption occurs upon interaction of the radiation with certain molecules, such as ozone (absorption of short-wave radiation - ultraviolet), water vapour, and carbon dioxide (absorption of long-wave radiation - infrared).

Due to these processes, out of the whole spectrum of solar radiation, only a small portion reaches the earth surface. Thus most of x-rays and other short-wave radiation is absorbed by atmospheric components in the ionosphere, ultraviolet is absorbed by ozone and not-so abundant long-wave radiation is absorbed by CO_2. As a result, the main wavelength range to be considered for solar applications is from 0.29 to 2.5 μm.

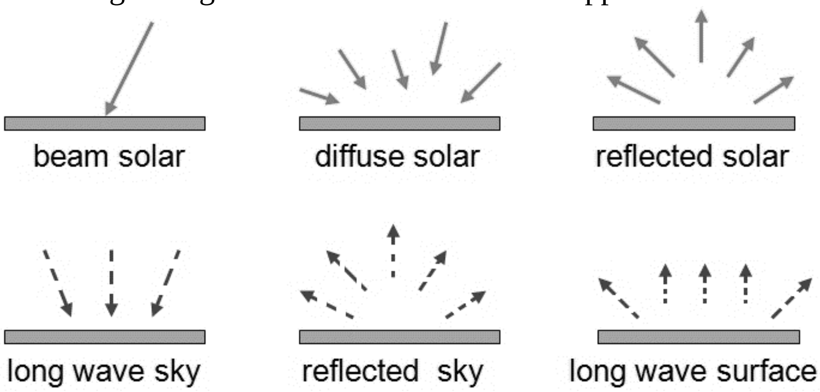


Fig.2.Different types of radiation at the earth surface: — short wave; - - long wave

India's solar installed capacity reached 34.404 GW as of 29 February 2020.

Insolation is the incident solar radiation onto some object. Specifically, it is a measure of the solar energy that is incident on a specified area over a set period of time. Generally insolation is expressed in two ways. One unit is kilowatt-hours per square meter (kWh/m^2) per day which represents the average amount of energy hitting an area each day. Another form is watts per square meter (W/m^2) which represents the average amount of power hitting an area over an entire year.

It is important to have values for insolation at certain positions on the Earth as these figures are used to help determine the size and output of solar power systems. Values for insolation can help to determine the expected output for solar panels and determine where on Earth solar panels would be most effective.

Radiation Measurement

The amount of solar radiation on the earth surface can be instrumentally measured, and precise measurements are important for providing background solar data for solar energy conversion applications. There are two important types of instruments to measure solar radiation:

1) Pyrheliometer 2) Pyranometer

Pyrheliometer is a device used for measuring direct beam radiation at normal incidence. Its outer structure looks like a long tube, projecting the image of a telescope and we have to point the lens to the sun to measure the radiance.

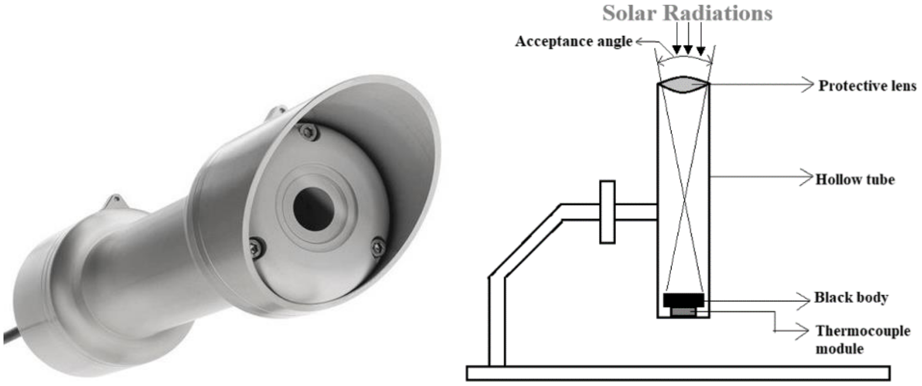


Fig. 3. Construction of Pyrheliometer

The lens is pointed towards the sun and the radiation will pass through the lens, tube and at the end falls on to the black object present at the bottom. A simpler diagram is shown in the Fig.4

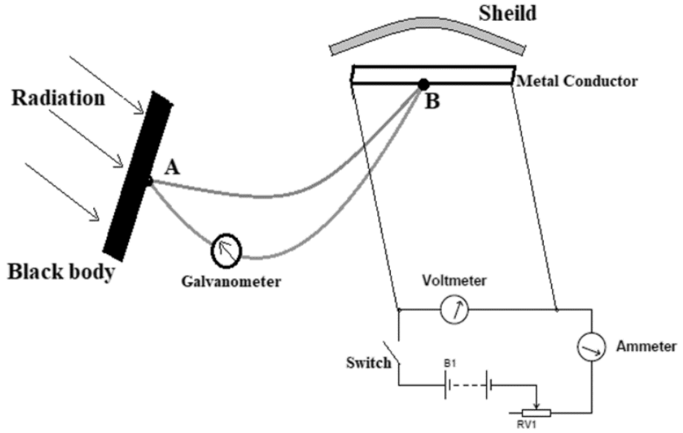


Fig.4. Simple diagram of Pyrheliometer

In the circuit, it can be seen that the black body absorbs the radiation falling from the lens and a perfect black body completely absorbs any radiation falling on it, so the radiation falling into the tube gets absorbed by the black object entirely. Once the radiation gets absorbed the atoms in the body gets excited because of the increasing temperature of the entire body. This temperature increase will also be experienced by the thermocouple junction ‘A’. Now with junction ‘A’ of the thermocouple at high temperature and junction ‘B’ at low temperature, a current flow takes place in its loop.(Thermocouple action) This current in the loop will also flow through the galvanometer which is in series and thereby causing a deviation in it. This deviation is proportional to current, which in turn is proportional to temperature difference at junctions.

The deviation in the galvanometer can be reduced by adjusting the rheostat to change the current in the Metal conductor. Now by adjusting the rheostat until the galvanometer deviation becomes completely void. Once this happens we can obtain voltage and current readings from the meters and do a simple calculation to determine the heat absorbed by the black body. This calculated value can be used to determine the radiation, as heat generated by the black body is directly proportional to the radiation.

-Top 5 Largest Solar Power Plants in India-
1. Pavagada Solar Park, Karnataka 2. Kurnool Ultra Mega Solar Park, Andhra Pradesh 3. Kamuthi Solar Power Project, Tamil Nadu 4. Bhadla Solar Park, Rajasthan 5. Charanka Solar Park, Gujarat

Pyranometer working and Construction

Pyranometer is a device that can be used to measure both beam radiation and diffused radiation. In other words, it is used to measure total hemispherical radiation (beam plus diffuse on a horizontal surface). The device looks like a saucer which is the best shape suited for its purpose. This device is more popular than the others and most of the solar resource data nowadays are measured using it. The original picture and internal structure of the Pyranometer is shown in Fig.5.

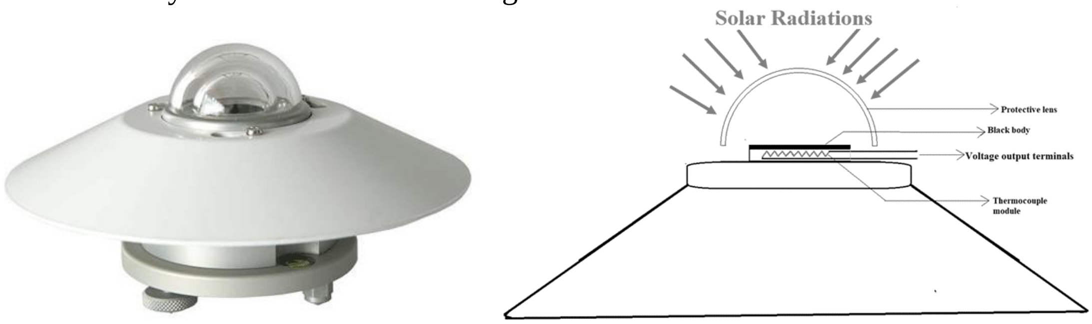


Fig.5. Pyranometer

Here the radiation from the surrounding atmosphere passes through the glass dome and falls onto the blackbody situated at the centre of the instrument. The temperature of the body rises after absorbing all the radiation and this rise will also be experienced by the Thermocouple chain or Thermocouple module present directly beneath the blackbody. So one side of the module will be hot and another will be cold because of the heat sink. The thermocouple module generates a voltage and this can be seen at the output terminals. This voltage received at the output terminals is directly proportional to temperature difference according to the principle of a thermocouple.

Since we know that the temperature difference is related to radiation absorbed by the black body, we can say the output voltage is linearly proportional to the radiation. Similar to the previous calculation, the value of total radiation can be easily obtained from this voltage value. Also by using the shade and following the same procedure, we can also obtain the diffused radiation. With total radiation and diffused radiation value, beam radiation value can also be calculated.

Quantum Sensors

Quantum sensors are specialized devices which measure the quantity of photosynthetically active radiation, or the portion of the visible spectrum which can be used by photosynthetic organisms, within a band of solar radiation. Specifically, quantum sensors measure the photosynthetic photon flux density (PPFD) of sunlight. This measurement is useful in agriculture for choosing productive farmland locations or maintaining growhouses and is also used in oceanography to calculate the boundaries of an ocean's sunlight zone. (For the latter reason, quantum sensors are often built with waterproof housing.) Quantum sensors typically use photovoltaic technology to generate a potential output.

Fig. 6. Quantum sensors

Solar Thermal Power Plant

Solar thermal power plant is a combination of solar energy and thermal energy. The sun's radiations is used as fuel in the power plant. Solar energy is converted into heat or thermal energy which is further converted to mechanical energy using turbine and electrical energy using generators. Further categories are based upon the power cycles i.e. low, medium and high temperature cycles. These cycles are based upon the solar radiations and type of collectors used for collecting the solar radiations. In low temperature cycles the temperature is limited to about 100^{o} C in medium temperature, range varies from 150^{o} C to 300^{o} C whereas in high temperature cycles temperature may go above 300^{o} C.

For different temperature cycle different thermodynamic cycles are used in the power plant. Generally, for low and medium temperature ranges, Rankine cycle is preferred whereas for high temperature range Brayton cycle is used. The cycle operation and different components of the solar thermal power plant are discussed here;

- Solar pond
- Solar energy collectors
- Working fluid
- Evaporator Boiler
- Turbine and Generator
- Condenser and Cooling tower

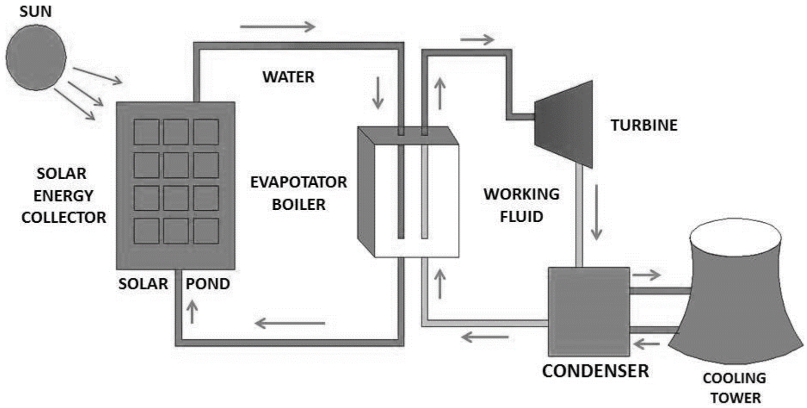


Fig.7. Solar thermal power plant

Solar pond: The solar energy coming from the sun is firstly absorbed by the solar pond. Solar pond is a reservoir of water where sun's rays directly focus by using solar energy collectors. After that, solar energy increases the internal energy and raises the temperature of solar pond. The fluid in the solar pond may be directly used as the working fluid if its temperature reaches up to evaporating temperature or other way is to use a secondary fluid known as working fluid. The fluid from the solar pond goes into cyclic process. The detailed operation of solar pond is as follows.

Solar pond, also called solar 'salt pond', is an artificially designed pond, filled with salty water, maintaining a definite concentration gradient. It combines solar energy radiation and sensible heat storage, and as such, it is utilised for collecting and storing solar energy. A solar pond reduces the convective and evaporative heat losses by reversing the temperature gradient with the help of non-uniform vertical concentration of salts.

The vertical configuration of "salt gradient solar pond" normally consists of the following three zones:

1. "Surface (homogeneous) convective zone (SCZ)"- It is adjacent to the surface and serves as a buffer zone between environmental fluctuations at the surface and conductive heat transport from the layer below. It is about 10 to 20 cm thick with a low uniform concentration at nearly the ambient air temperature.
2. "Lower connective zone (LCZ)"- It is at the bottom of the pond and this is the layer with highest salt concentration, where high temperatures are built up.
3. "Concentration/Intermediate gradient zone (CGZ)"- This zone keeps the two convective zones (SCZ and LCZ) apart and gives the solar pond its unique thermal performance. It provides excellent insulation for the storage layer, while transmitting the solar radiation. To maintain a solar pond in this non-equilibrium stationary state it is necessary to replace the amount of salt that is transported by molecular diffusion from the LCZ to SCZ. This means that salt must be added to the LCZ, and fresh water to the

SCG whilst brine is removed. The brine can be recycled, divided into water and salt (by solar distillation) and returned to the pond.

The major heat loss occurs from the surface of the solar pond. This heat loss can be prevented by spreading a plastic grid over the pond's surface to prevent disturbance by the wind. Disturbed water tends to lose heat transfer faster than when calm.

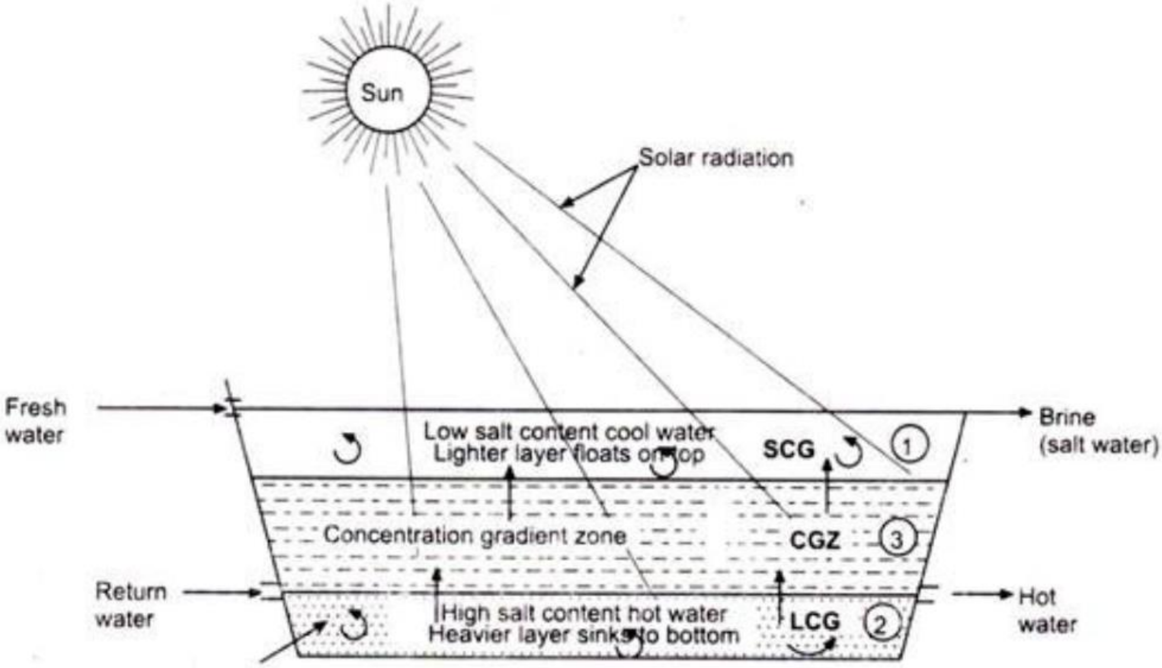


Fig.8. Principle of Solar Pond

Principle of Solar Pond

Due to the excessively high salt concentration of the LCZ, a plastic liner or impermeable soil must be used to prevent infiltration into the nearby ground water or soil. The liner is a factor that increases the cost of a solar pond. A site where the soil is naturally impermeable, such as the base of a natural pond or lake, or can be made impermeable by compaction or other means, will allow considerably lower power costs.

The optical transmission properties and related collection efficiency vary greatly and depend on the following factors:

i. Salt concentration.
ii. The quantity of suspended dust or other particles.
iii. Surface impurities like leaves or debris, biological material like bacteria and algae.
iv. The type of salt.

It becomes obvious that much higher efficiencies and storage can be achieved through the utilization of refined or pure salt whenever possible, as this maximizes optical transmission.

The solar pond is an effective collector of diffuse, as well as direct radiation, and will gather useful heat even on cloudy or overcast days. Under ideal conditions, the pond's absorption efficiency can reach 50% of incoming solar radiation, although actual efficiencies average about 20% due to heat losses.

Applications of Solar Ponds:

1. Power generation.
2. Space heating and cooling.
3. Crop drying.
4. Desalination.
5. Process heat.

Limitations of Solar Ponds:

1. Sunny climate is required
2. Need for large land area.
3. Availability of salt.
4. Availability of water.

Solar energy is a completely free source of energy and it is found in abundance. Though the sun is 90 million miles from the earth, it takes less than 10 minutes for light to travel from that much of distance.

Solar energy collectors: Solar energy collectors are the device used for collecting the solar radiations and focus the solar radiations at particular location to transfer the heat energy into the solar ponds or fluid. Generally, two types of collectors are used first is non-concentrating or flat plate type solar collector which is used for low temperature cycle and second one is concentrating or focusing type solar collector which are used for medium and high temperature applications. Collectors make the solar energy more useful. Flat plate collectors are very simple, the collecting area is equal to absorbing area where as focusing type collector have several arrangements of mirrors and lenses for proper concentration of sun light. Due to this by using focus type collectors we can capture 100 times solar radiation as compared to flat plate collector keeping the area same. By using focusing type collector we can directly generate medium pressure steam.

Solar collectors are classified as

1. Non concentrating type
    - i) Flat-Plate Collectors
    - ii) Evacuated-Tube Collector
2. Concentrating type
    - i) Parabolic trough collector.
    - ii) Power tower receiver.
    - iii) Parabolic dish collector.
    - iv) Fresnel lens collector.

Flat-Plate Collectors

Flat-plate solar collectors are the most common ones. They consist of an absorber, a transparent cover and insulation. The main use of the technology is usually in residential buildings where the demand for hot water is big and affects bills. Commercial application of flat-plate collectors is usually seen in car washes, laundromats, military laundry facilities or restaurants.

The parts of a flat plate collectors are

- Black surface - absorbent of the incident solar energy
- Glazing cover - a transparent layer that transmits radiation to the absorber, but prevents radiative and convective heat loss from the surface
- Tubes containing heating fluid to transfer the heat from the collector
- Support structure to protect the components and hold them in place
- Insulation covering sides and bottom of the collector to reduce heat losses

Flat-plate solar collectors show a good price-performance ratio and also give a lot of mounting options.

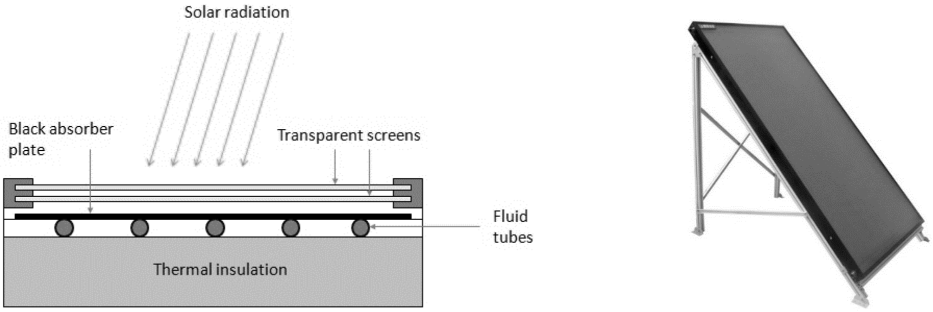


Fig. 9. Flat plate collectors

-Top 10 Solar Companies in India- *Adani Power, Tata Solar, Jinko Solar, Trina Solar, ACME Solar, Vikram Solar, Waaree Energies, EMMVEE, Goldi Solar, Canadian Solar*

Evacuated-Tube Collector

This is a type of a vacuum collector. Its absorber strip is placed in an evacuated and pressure proof glass tube. The heat transfer fluid flows directly the absorber into a U-tube or in a tube-in-tube system. The heat pipe collector integrates a special fluid, which evaporates even at low temperatures, thus the steam rises in the individual heat pipes and warms up the fluid in the main pipe, generating heat. Thermodynamic panels are also based on such a refrigerant fluid but are exploiting the heat in the ambient air, and, therefore, are only suitable for hot water.

The technology is very reliable as it has an estimated lifespan of 25 years. The vacuum that surrounds the outside of the tubes greatly reduces the risk of heat loss, therefore efficiency is greater than it is with flat-plate collectors.

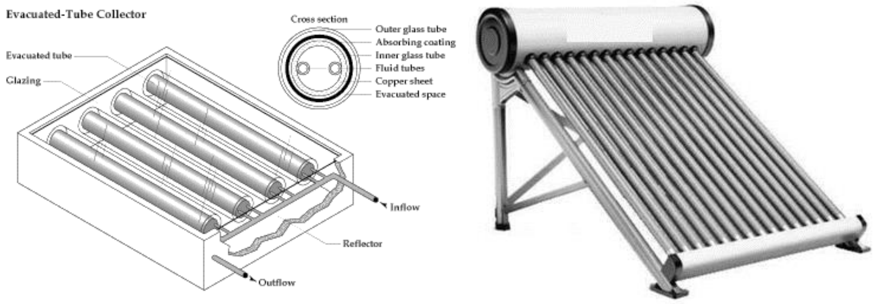


Fig. 10. Evacuated-Tube Collector

Parabolic Trough Collector

- It is a line focusing type collector. In this type of collector, the solar radiations falling on the area of the parabolic reflector are concentrated at the focus of the parabola.
- When the reflector is manufactured in the form of a trough with the parabolic cross-section, the solar radiations gets focused along a line. An absorber pipe is placed along this line and a working fluid (usually synthetic oil or water) flows through it.
- When the focused solar radiations fall on the absorber pipe, it heats the fluid to a high temperature. Then the heat absorbed by the working fluid is transferred to water for producing steam.
- The focus of solar radiations changes with the change in sun's elevation. In order to focus the solar radiations on the absorber pipe, either the trough or the collector pipe is rotated continuously about the axis of the absorber pipe.

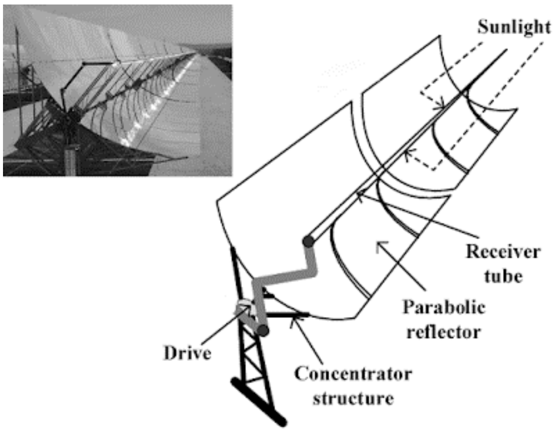


Fig.11. Parabolic Trough Collector

Power Tower Receiver

In this collector, the receiver is located at the top of the tower. It has a large number of independently-moving flat mirrors (heliostats) spread over a large area of ground to focus the reflected solar radiations on the receiver. The heliostats are installed all around the central tower. Each heliostat is rotated into two directions so as to track the sun. The solar radiations reflected from heliostats are absorbed by the receiver mounted on a tower of about 500 m height. The tower supports a bundle of vertical tubes containing the working fluid. The working fluid in the absorber receiver is converted into the high-temperature steam of about 600^{o}C – 700^{o}C. This steam is supplied to a conventional steam power plant coupled to an electric generator to generate electric power.

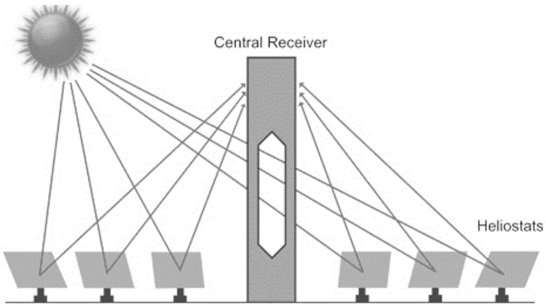
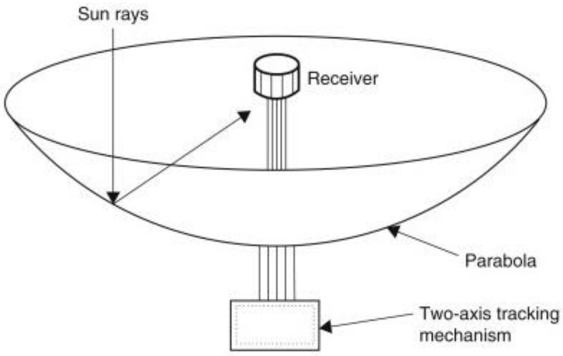


Fig.12. Power tower receiver

Parabolic Dish Collector

- In these collectors, the receiver is placed at the focal point of the concentrator. The solar beam radiations are focused at a point where the receiver (absorber) is placed. The solar radiations are collected in the receiver.
- A small volume of fluid is heated in the receiver to a high temperature. This heat is used to run a prime mover coupled with a generator.
- A typical parabolic dish collector has a dish of 6 m diameter. This collector requires two-axis tracking. It can yield temperatures up to 3000^{o} C.
- Due to the limitations of size and the small quantity of fluid, dish type solar collectors are suitable for only small power generation (up to few kW).



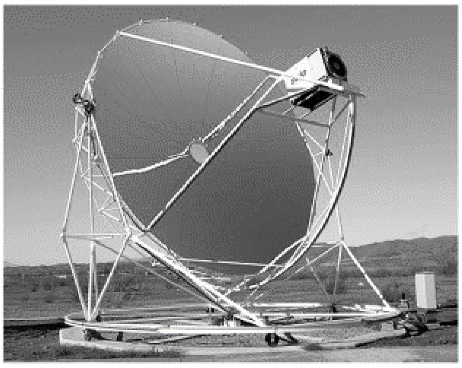


Fig.13. Parabolic Dish Collector

Fresnel Lens Concentrating Collector

- In this collector, a Fresnel lens which consists of fine, linear grooves on the surface of refracting material of optical quality on one side and flat on the other side is used.
- The angle of each groove is so designed that the optical behaviour of the Fresnel lens is similar to that of a common lens.
- The solar radiations which fall normally to the lens are refracted by the lens and are focused on a line where the absorber tube (receiver) is placed to absorb solar radiations.

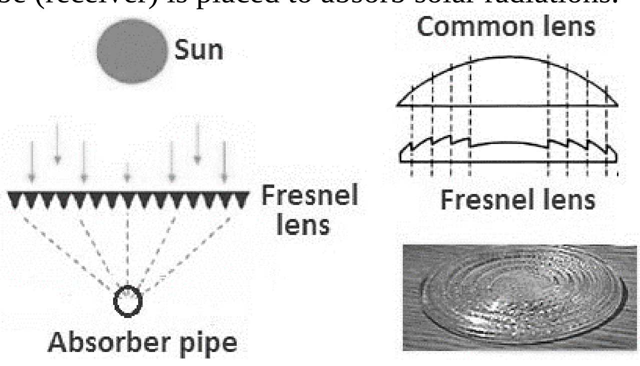


Fig.14. Fresnel Lens Concentrating Collector

Working Fluid: It is the fluid used in the cyclic operation. We use some other fluid as a working fluid because sometimes solar energy is not capable to evaporate the water. We use working fluid which gains energy from the solar pond and evaporate easily or having evaporation temperature less as compare to water. Generally, brine or some organic fluids are used as the working fluid. After evaporation working fluid goes through cyclic operations in turbine and then through condenser it goes again into the evaporator boiler. The cycle is continuously repeated.

Evaporator Boiler: In this device, working fluid is kept and gains latent heat of vaporisation from the sun's radiations or by solar pond. Working fluid is circulating throughout the cycle by evaporating boiler.

Turbine and Generator: Turbine and generators are the essential part of the power generation system. Working fluid goes through the cyclic operation and runs the turbine which is connected to the generator. Generator generates electricity which is transferred to the required location.

Condenser and cooling tower: After turbine, the working fluid goes into the condenser and cooling tower condenses the working fluid and sends back to the evaporator boiler with the help of pump.

Working of solar power plant

The working is very simple almost similar to any thermal power plant. Solar power plant also works on Rankine cycle and Brayton cycle as per the requirements. With the help of construction, we can easily predict the cycle of operation and working. Working fluid gains latent heat of vaporisation from the direct solar radiations or by means of solar ponds in the evaporator boiling and converts it into vapour form. After that it runs the turbine which is connected to the generator. Then the turbine working fluid goes into the condenser and loses heat and again sends back to the evaporator boiler with the help of pump. This whole cycle repeats continuously until the sun remains in the sky and radiation falls on the earth surface.

Advantages:

- Solar power plants work on solar energy which is available in abundant on the earth surface at most of the places.
- Solar power plants produce negligible pollution as compared to thermal power plant.
- The energy produced is renewable energy with negligible cost.
- Quantity of water used in solar power plants is very less as compare to other power plants.

Disadvantages:

- The major drawback is the availability of the sun. Sun's radiation of desired intensity is not available whole day.
- For collecting the sun radiations at useful rate large area is required.
- Initial setup cost of Solar plant is quite high.

It would cost anywhere between Rs 70,000 to Rs 1,20,000 per kW depending on the panels and inverter

Central Receiver Power Plants

Unlike linear concentrating systems (troughs), which reflect light onto a focal line, the central receiver systems send concentrated light onto a remote central receiver. A typical example of such a system is a solar power tower system, which consists of multiple tracking mirrors (heliostats) positioned in the field around a main external receiver installed on a tower. Such systems are capable of reaching of much higher levels of concentration than linear systems. Concentrated radiation is further used as heat to produce steam and convert it to electricity (like in a regular power plant), or the generated thermal energy can be stored in a molten salt storage.

Central receiver systems are typically large-scale plants that are usually built to power a steam cycle. The central position of the receiver offers a universal advantage to collect all energy at one location and save on transport networks. Central receiver systems use a field of distributed, circular array of mirrors that is, heliostats which individually track the sun and focus the sunlight on the top of a tower. By concentrating the sunlight 600 – 1000 times, they achieve temperatures from 800°C to well over 1000°C. Solar energy is absorbed by a working fluid and then used to generate steam to power a conventional turbine. The high temperatures available in solar towers can be used not only to drive steam cycles, but also for gas turbines and combined cycle systems. Such systems can achieve up to 35% peak and 25% annual solar electric efficiency when coupled to a combined cycle power plant.

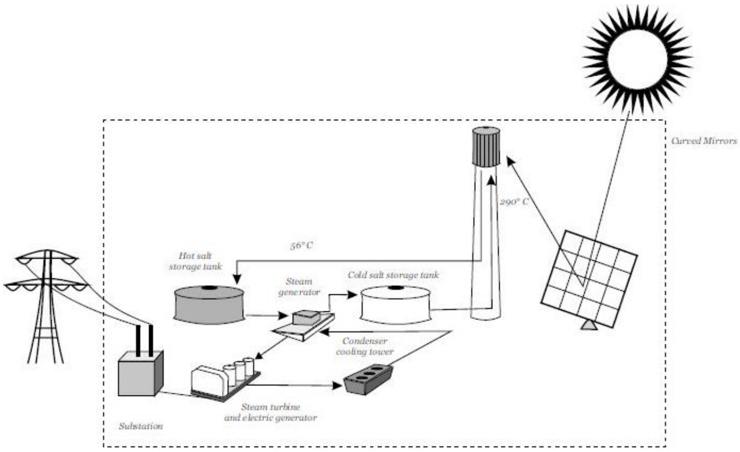


Fig.15. Operation of Central Receiver Power Plants

Major sub-components of central receiver system

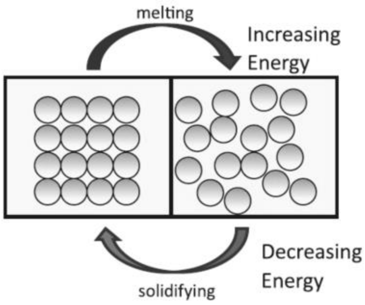
- **Heliostat field:** The heliostat field comprises a large heliostat, structure, and control/tracking. The heliostat typically utilizes a mirror, which can be oriented throughout the day to redirect sunlight along a fixed axis toward a stationary target or receiver. The reflecting element of a heliostat is typically a thin, back (second) surface, low-iron glass mirror. This heliostat is composed of several mirror module panels rather than a single large mirror. The thin glass mirrors are supported by a substrate backing to form a slightly concave mirror surface. Individual panels on the heliostat are also canted toward a point on the receiver. The heliostat focal length is approximately equal to the distance from the receiver to the farthest heliostat. Subsequent “tuning” of the closer mirrors is possible.
- **Storage:** Central tower based systems typically use Molten salt, hot concrete storage, phase change materials, saturated steam or pressurized air as storage media.
    - Nitrate salt mixtures can be used as both a heat transfer fluid and a storage medium at temperatures of up to 565°C. However, most mixtures currently being considered freeze at temperatures around 140 to 220°C and thus must be heated when the system is shutdown. They have a good storage potential because of their high volumetric heat capacity.
    - Liquid sodium can also be used as both a heat transfer fluid and storage medium, with a maximum operating temperature of 600°C. Because sodium is liquid at this temperature, its vapour pressure is low. However, it solidifies at 98°C thereby requiring heating on shutdown. The cost of sodium-based systems is higher than the nitrate salt systems.
    - For high-temperature applications such as Brayton cycles, it is proposed to use air or helium as the heat transfer fluid. Operating temperatures of around 850°C at 12 atm pressure are being proposed. Although the cost of these gases would be low, they cannot be used for storage and require very large diameter piping to transport them through the system.
- **Receivers/absorber and power block:** This includes the receivers, absorbers including heat collection elements, and Power Block. The receiver, placed at the top of a tower, is located at a point where reflected energy from the heliostats can be intercepted most efficiently. The receiver absorbs the energy being reflected from the heliostat field and transfers it into a heat transfer fluid. There are two basic types of receivers: external and cavity.
    - **External Receivers.** These normally consist of panels of many small (20-56 mm) vertical tubes welded side by side to approximate a cylinder. The bottoms and tops of the vertical tubes are connected to headers that supply heat transfer fluid to the bottom of each tube and collect the heated fluid from the top of the tubes.
    - **Cavity Receivers.** In an attempt to reduce heat loss from the receiver, some designs propose to place the flux absorbing surface inside of an insulated cavity, thereby reducing the convective heat losses from the absorber. The flux from the heliostat field is reflected through an aperture onto absorbing surfaces forming the walls of the cavity. Typical designs have an aperture area of about one-third to one-half of the internal absorbing surface area. Cavity receivers are limited to an acceptance angle of 60 to 120 degrees. Therefore, either multiple cavities are placed adjacent to each other, or the heliostat field is limited to the view of the cavity aperture.

The solar field which consists of solar collectors, balance of system and tracking constitutes 36% of the cost followed by the power block at 24% which comprises the turbine, generator, heat exchangers etc. The receiver is also a major component of this technology comprising 15% of the cost.

Thermal Energy storage system with PCM

Phase change materials (PCMs) are materials that undergo the solid-liquid phase transformation, more commonly known as the melting-solidification cycle, at a temperature within the operating range of a selected thermal application. As a material changes phase from a solid to a liquid, it absorbs energy from its surroundings while remaining at a constant or nearly constant temperature. The energy that is absorbed by the material acts to increase the energy of the constituent atoms or molecules, increasing their vibrational state. At the melt temperature the atomic bonds loosen and the materials transitions from a solid to a liquid.

Solidification is the reverse of this process, during which the material transfers energy to its surroundings and the molecules lose energy and order themselves into their solid phase. This can be seen in Fig. 16.a. The energy that is either absorbed or released during the melting-solidification cycle is known as the latent heat of fusion. Latent heat is unique in that it is heat that is absorbed into a material without the material itself increasing in temperature.



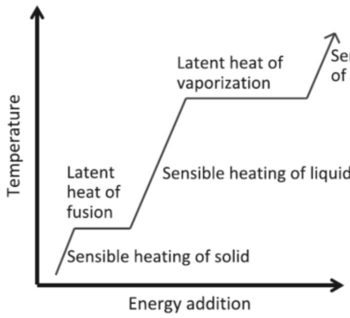


Fig. 16.a. The melting solidification process **b. Standard heating curve**

It is easy to picture this process by considering the melting of an ice cube. You can heat the ice cube by exposing it to ambient room temperature conditions, by heating it with a hair dryer, or by blasting it with a blow torch, but no matter how much heat flux is supplied to it, that ice cube will not increase in temperature until the melting process is complete. The latent heat absorbed during the melting process is referred to as the latent heat of fusion, in order to distinguish it from the other form of latent heat, the latent heat of vaporization, which characterizes the change in phase from a liquid to a gas. In contrast to latent heat, which does not increase the temperature of a material, sensible heat is that heat which does result in a change in temperature within the material.

A standard continuous heating process may begin with a subcooled solid, which is heated to the melting point through sensible heating. As the heating process continues the solid transitions to a liquid through the latent of heat fusion, and sensible heat then increases its temperature to the boiling point. Once the boiling point is reached, the liquid transitions to a vapour through the latent heat of vaporization until the phase change process is complete. Any additional heating is now in the form of sensible heat which acts to superheat the vapour. It can be seen in Fig. 16.b that the latent heat of vaporization is a higher energy process than the latent heat of fusion.

It is true that in general that the boiling/condensation process absorbs/and releases more energy, but the density change from a liquid to a vapour is large, and working with boilers and condensers often requires a significant amount of support equipment which is not always convenient. There are of course many applications for boiling heat transfer, but here we will concentrate on the applications for which a solid-liquid phase change process is most advantageous. The amount of energy absorption or release during the melting-solidification cycle is governed by the value of that material's latent heat of fusion. The latent heat of fusion is commonly expressed in units of J/g or kJ/kg. Thus the process is a mass-based process. The amount of energy absorbed by the material during melting depends solely on the mass of material present in the design.

Advantages of PCMs

- The use of PCMs for transient thermal management has the advantage of maintaining a constant system temperature throughout the melt process regardless of applied heat flux.
- PCMs are lightweight, portable and highly reliable depending only on the characteristics of the material itself, and do not depend on an external flow source such as a fan or pump.
- The main options available for thermal energy storage include sensible heat storage and thermochemical storage.
- Latent heat storage has a much higher energy density than sensible heat storage, resulting in less required material mass and/or smaller storage tank volumes.
- Latent heat storage systems are also easier to work with than thermochemical storage.
- The solid-liquid transition results in only a small density change, resulting in smaller system size and less support equipment than when attempting to store thermal energy for long term use through the liquid vapour phase change process.

Limitations

PCMs, however, are far from perfect solutions. The detriment most commonly cited to their greater utilization is that many PCMs do not have high thermal conductivities or diffusivities, preventing rapid system transients.

Application of PCM in Concentrating Solar Power Plants

The use of phase change materials for thermal energy storage (TES) in solar applications can extend the usefulness of the technology so that benefits can be provided even where there is low or no direct insolation. Commercial solar power plants are designed using the concept of Concentrating Solar Power (CSP). In these plants, sunlight is reflected and concentrated using mirrors and then used to heat a carrier fluid. An example of parabolic trough technology is shown in Fig. 17. In this image, the thermal receiver is supported above the concentrating mirrors. The receiver is a black pipe encased in a vacuum tube to reduce convective losses.

A high temperature, high pressure heat transfer fluid (HTF) circulates through the receiver pipes. Depending on the design of the system, the HTF fluid may serve as the heat source in an evaporator, creating steam which powers a stream turbine which drives a generator, or the HTF may directly vaporize as it passes through the solar field and then pass straight through the turbine without an intermediate heat exchanger (known as Direct Steam Generation—DSG). In either design, during periods of high insolation, it is possible to absorb more solar thermal energy into the HTF than is necessary to power the turbine. This "excess" solar thermal energy can be stored using sensible or latent heat in storage tanks as shown in Fig. 17.

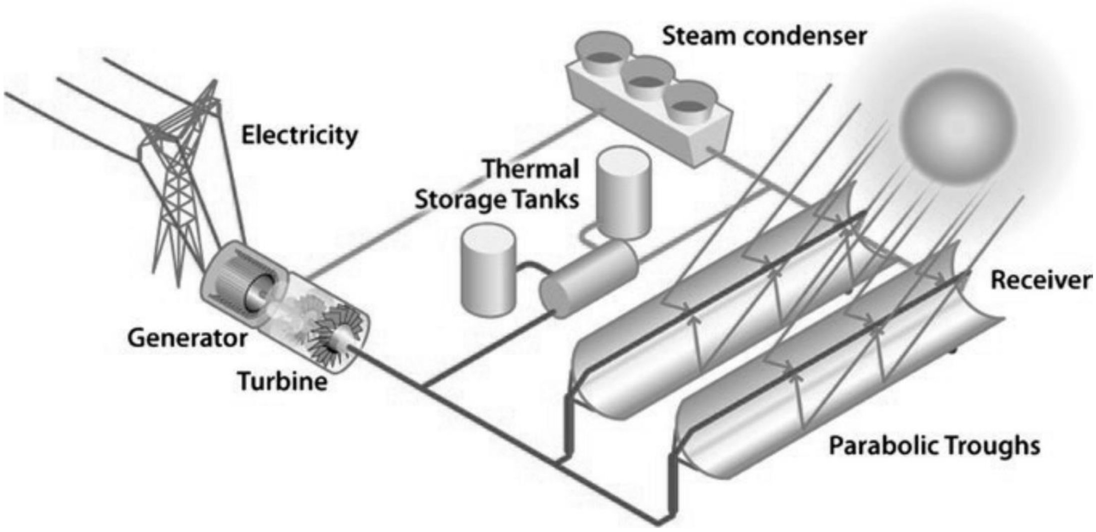


Fig. 17. Direct steam generation concentrating solar power plant with thermal energy storage

In the two-tank molten system a heat exchanger is located between the two tanks with the HTF flowing on one side of the exchanger and the storage medium (molten salt) on the other side. During the energy storage cycle, some of the HTF from the solar is diverted to this exchanger where it transfers energy to the molten salt. In this case, the salt flow originates in the "cold" tank and flows through the heat exchanger where it absorbs solar thermal energy and then into the "hot" tank where it is stored. During the energy discharge cycle, the HTF and molten salt flow paths are reversed.

The salt gives up its energy to the HTF as it moves from the hot tank through the heat exchanger into the cold tank, and the now hot HTF is used in the power cycle. While these systems have seen success, there is significant cost inherent in using two storage tanks, and the energy density of these storage systems is low as the salt remains in the liquid phase at all times. The use of PCMs in these applications can thus reduce tank number (to one), size and installation costs, creating an economic benefit. Molten salts are commonly used in these applications because of their high operating points. These materials have melting points from around 300 °C to over 800 °C. The HTF in parabolic trough and linear Fresnel system can reach around 300–400 °C in the receiver, while heliostats receivers can operate in excess of 2000 °C. Salts are well suited for these operational ranges, but suffer from a few drawbacks including high corrosiveness and low thermal conductivity. The primary issue with low thermal conductivity is the need for quick charge and discharge of energy as the HTF flows through the storage medium. In a few cases, liquid metal alloys may be used instead of molten salts.

The PCM used in the Rankine cycle system was 60 % $NaNO_3$/40 % KNO_3, known as solar salt while the PCM used with the s-CO2 power cycle was $KCl/MgCl_2$. The typical PCMs used in these applications are inorganic salts which melt in the range from 300–800 °C. These PCMs tend to be corrosive and have low thermal conductivities but it was shown that this can be offset with the use of embedded heat pipes or thermosyphons. In certain applications liquid metals may be used instead.

Domestic Solar Applications

While the large CSP plants certainly have significant technical and economic incentives to implement PCM thermal energy storage systems, smaller scale solar systems can also reap some benefits from TES. For example, solar thermal systems can be used by small businesses and homes for hot water production and for heating systems. A small scale solar hot water system with energy storage can be seen in Fig. 18. These systems feature a flat plate solar collector, typically mounted on the roof, which features a heat transfer fluid passing through the receiver tubes.

The receiver tubes are isolated within an enclosure with a glass cover plate. The enclosure may be evacuated to prevent convective losses. In many ways this is similar to the CSP solar field, but without the concentrators. The lack of concentrators means that the HTF will not reach the high temperatures characteristic of CSP. As such the fluid can't be used to create vapour and drive a power system, but is hot enough to provide the heat source for a domestic hot water tank. As with CSP, the effectiveness of the system is limited to daylight hours, but the solar thermal system can be designed to store extra heat using PCM in the storage tanks for the overnight hours, greatly reducing dependence on supplemental natural gas or electrical heating.

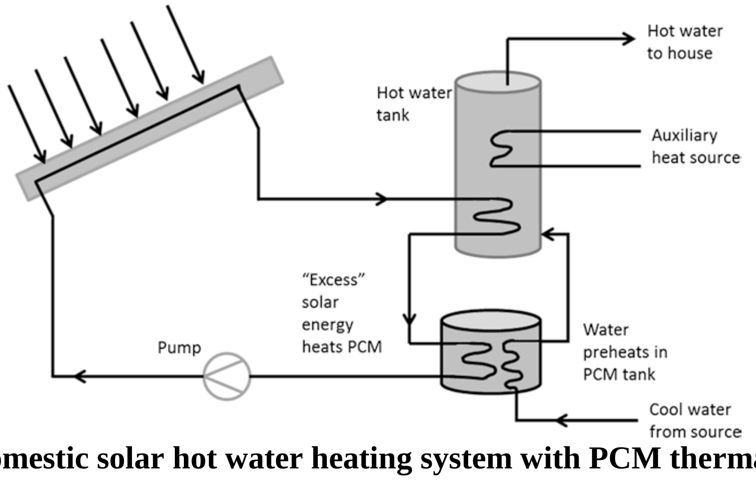


Fig.18. Domestic solar hot water heating system with PCM thermal storage

The average cost of installation of rooftop PV system without subsidy is around Rs 60,000 – 70,000. After availing 30 per cent subsidy, people just have to pay Rs 42,000 – 49,000 for installing a rooftop PV system.

Solar Photovoltaic systems: Basic Principle of SPV conversion

A photovoltaic (PV) cell is an energy harvesting technology that converts solar energy into useful electricity (DC) through a process called the photovoltaic effect. It is made up of semiconductor materials such as silicon, gallium arsenide and cadmium telluride, etc. These cells vary in size ranging from about 0.5 inches to 4 inches. There are different types of PV cells which all use semiconductors to interact with incoming photons from the Sun in order to generate an electric current.

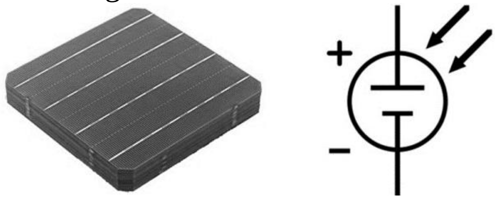


Fig. 19 PV cell and PV Cell symbol

Photovoltaic cell concepts: Cell
Layers of a PV Cell

A photovoltaic cell is comprised of many layers of materials, each with a specific purpose. The most important layer of a photovoltaic cell is the specially treated semiconductor layer. It is comprised of two distinct layers of p-type and n-type, and is what actually converts the Sun's energy into useful electricity through a process called the photovoltaic effect. On either side of the semiconductor is a layer of conducting material which "collects" the electricity produced. Note that the backside or shaded side of the cell can afford to be completely covered in the conductor, whereas the front or illuminated side must use the conductors sparingly to avoid blocking too much of the Sun's radiation from reaching the semiconductor.

The final layer which is applied only to the illuminated side of the cell is the anti-reflection coating. Since all semiconductors are naturally reflective, reflection loss can be significant. The solution is to use one or several layers of an anti-reflection coating (similar to those used for eyeglasses and cameras) to reduce the amount of solar radiation that is reflected off the surface of the cell.

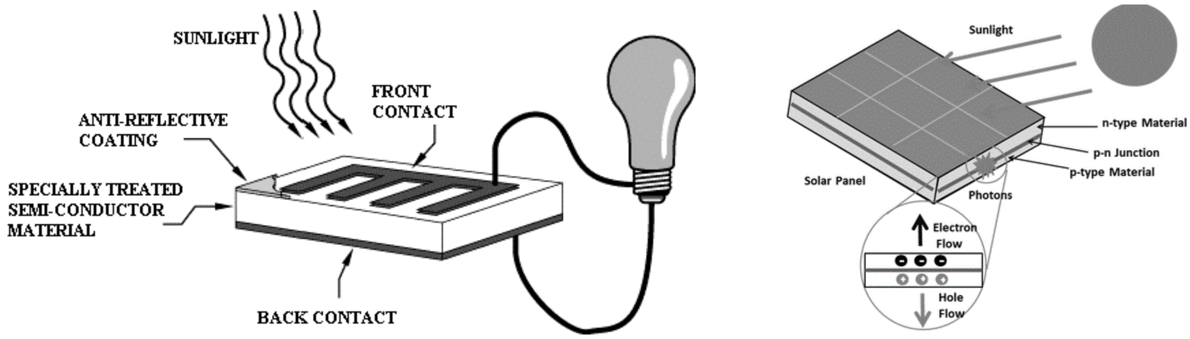


Fig. 20. A diagram showing the photovoltaic effect.

Photovoltaic Effect

The photovoltaic effect is a process that generates voltage or electric current in a photovoltaic cell when it is exposed to sunlight. These solar cells are composed of two different types of semiconductors—a p-type and an n-type that are joined together to create a p-n junction. By joining these two types of semiconductors, an electric field is formed in the region of the junction as electrons move to the positive p-side and holes move to the negative n-side. This field causes negatively charged particles to move in one direction and positively charged particles in the other direction.

Light is composed of photons, which are simply small bundles of electromagnetic radiation or energy. When light of a suitable wavelength is incident on these cells, energy from the photon is transferred to an electron of the semiconducting material, causing it to jump to a higher energy state known as the conduction band. In their excited state in the conduction band, these electrons are free to move through the material, and it is this motion of the electron that creates an electric current in the cell.

- **Cell:** A photovoltaic cell is the most basic unit of a solar PV system - solar cells can be either monocrystalline or polycrystalline, and their key characteristic is that they produce a voltage output when exposed to light. It is important to note that although they are normally called "solar cells", they can respond to any type of light. Each cell produces approximately 1/2 a volt and a solar module can have any number of solar cells.

- **Module:** A photovoltaic module consists of multiple PV cells connected in series to provide a higher voltage output. PV modules are manufactured in standard sizes. A solar module designed for charging a 12 volt battery will typically have 36 solar cells while the typical residential grid connected system uses solar modules with 60 solar cells. For large commercial and utility scale solar systems, solar modules will have typically 72 solar cells. By increasing the number of solar cells the module voltage and wattage increases. The term solar panel is sometimes used interchangeably with solar module. The main difference is that some solar panels models are composed of multiple modules mounted together.
- **Array:** A photovoltaic array is a system composed of multiple PV modules. They can be connected in one or more series circuits, which are connected to a combiner box to provide a single direct-current output. This output can be used to charge batteries, power DC loads, or fed to an inverter to provide an AC voltage for home appliances or exporting to the electric grid.

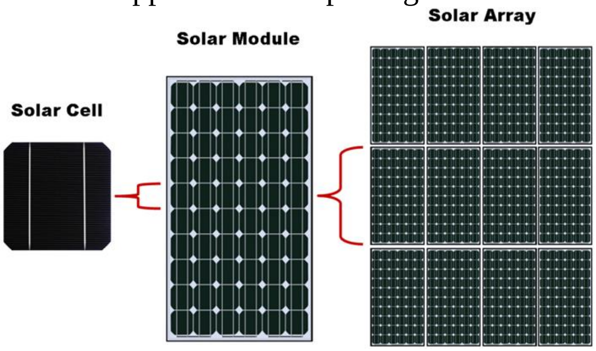


Fig.21. Cell module and array

Operation of PV Systems

Solar cells produce direct current (DC), therefore they are only used for DC equipments. If alternating current (AC) is needed for AC equipment or backup energy is needed, solar photovoltaic systems require other components in addition to solar modules. These components are specially designed to integrate into solar PV system. The components of solar photovoltaic system are shown in the figure.

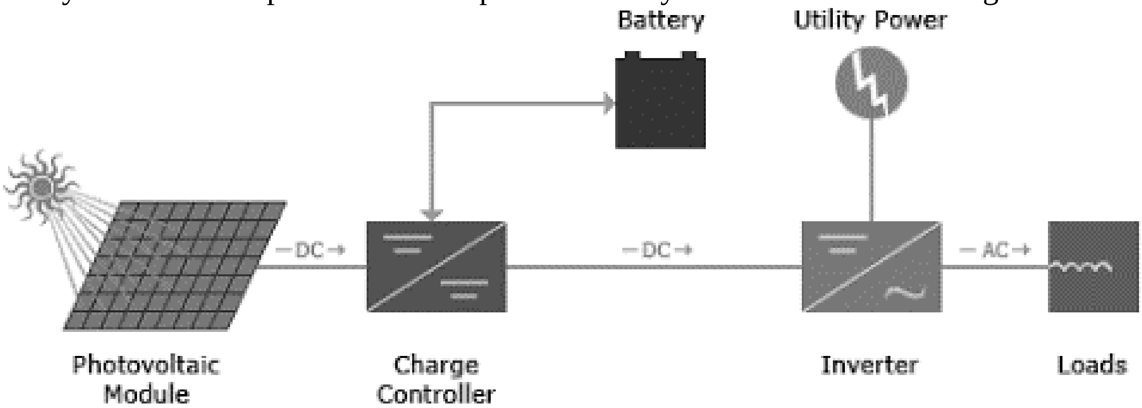


Fig. 22. Components of Photovoltaic system

1. **Solar or Photovoltaic Module** is the essential component of any solar PV system that converts sunlight directly into DC electricity.
2. **Solar Charge Controller** regulates voltage and current from solar arrays, charges the battery, prevents battery from overcharging and also performs controlled over discharges.
3. **Battery** stores the energy produced from solar arrays for using when sunlight is not visible, night time or other purposes.
4. **Inverter** is a critical component of any solar PV system that converts DC power output of solar arrays into AC for AC appliances.
5. **Lightning protection** prevents electrical equipment from damages caused by lightning or induction of high voltage surge. It is required for the large size and critical solar PV systems, which include efficient grounding.

Net metering is a billing mechanism that credits solar energy system owners for the electricity they add to the grid.

Types of PV Systems

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principle classifications are grid-connected or utility-interactive systems and stand-alone systems. Photovoltaic systems can be designed to provide DC and/or AC power service, can operate interconnected with or independent of the utility grid, and can be connected with other energy sources and energy storage systems.

PV Direct System

These are the simple most type of solar PV systems, with the fewest components; the Solar Panels and the load. Because they don't have batteries and are not hooked up to the grid, they only power the loads when the sun is shining. They are appropriate for a few applications e.g. water pumping or attic ventilation fan.

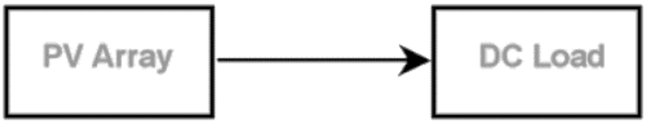


Fig. 23. Direct PV System

Solar Off Grid System

Also referred to as stand-alone systems, it is designed to be independent of the power grid. Batteries are used to store energy when the sun is not available during cloudy days or at night. This type of system will require regular attention to battery electrolyte levels and terminal corrosion.

- Independence from the utility grid
- Not subject to the terms/policies of the utility company
- Rate increases, blackouts, or brownouts do not apply
- In remote areas, it is cost effective than extending a grid
- Encourages energy efficiency
- Batteries require maintenance and has limited life
- More components means more complexity
- Batteries decrease system efficiency
- It is more expensive than a grid-direct system
- When the batteries are fully charged, potential power from the PV array is not utilized
- If the PV system fails, back-up electricity is required to run load
- Most off-grid systems use a backup generator for non-sunny days. They are expensive, noisy, dirty, and require fuel and regular maintenance

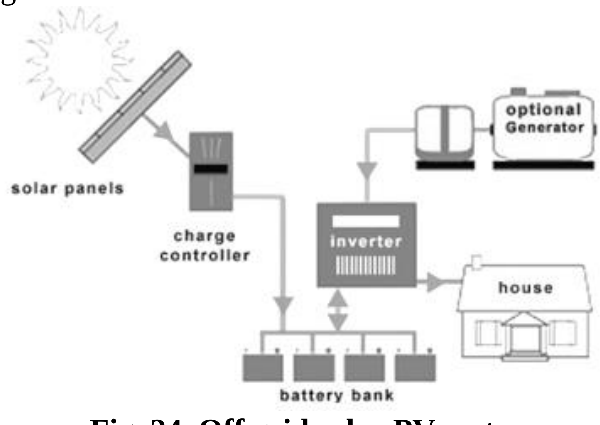


Fig. 24. Off grid solar PV system

Solar Grid Tied System without Battery backup

These are most common type of PV systems. They are also known as on-grid, grid-tied, grid-intertied, or grid-direct systems. They generate solar electricity and route it to the loads and to the grid, offsetting some of electricity usage. System components comprises of the PV array and inverter. Grid-connected system is similar to regular electric powered system except that some or all of the electricity comes from the sun. The drawback of these battery less systems is that they provide no outage protection when the utility grid fails, these systems cannot operate.

- grid-tied-system
- Increased design flexibility because the system does not have to power all of the home's loads
- It is less expensive compared to stand-alone or grid-tied with battery backup systems
- It requires the least amount of maintenance
- If the system produces more than the loads need, then the extra energy is exchanged with the grid
- Grid-direct systems have a higher efficiency because batteries are not part of the system
- Higher voltage means smaller wire size
- Electricity costs are fixed for the life of your system
- There is no power to the home when the grid goes down
- Paperwork requirements for interconnection, incentives, and rebates

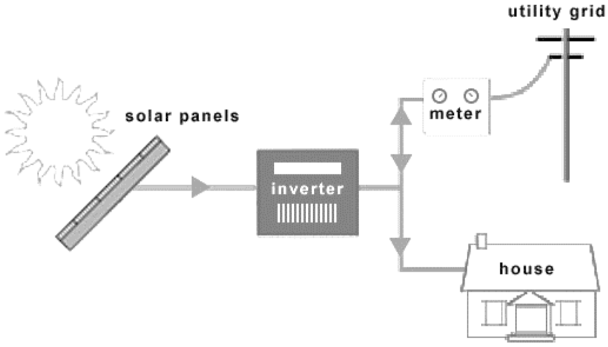


Fig. 25. Grid tied system without battery back up

Solar Grid Tied with Battery Backup System

This type is very similar to an off-grid system in design and components, but adds the utility grid, which reduces the need for the system to provide all the energy all the time.

- grid-tied-with-battery-backup
- Designated loads have power when the grid goes down
- If the system produces more than the home needs, then the extra energy is sold back to the utility-not lost as in a stand-alone systems after the batteries get full on a sunny day
- Batteries require maintenance
- Requires rewiring circuits from main service panel to a separate subpanel
- More components mean more complexity
- Batteries decrease system performance because of their efficiency losses
- More expensive than a grid-direct system
- Typically only provides modest backup – usually not all of the loads are backed up
- Requires paperwork for interconnection, incentives, and rebates

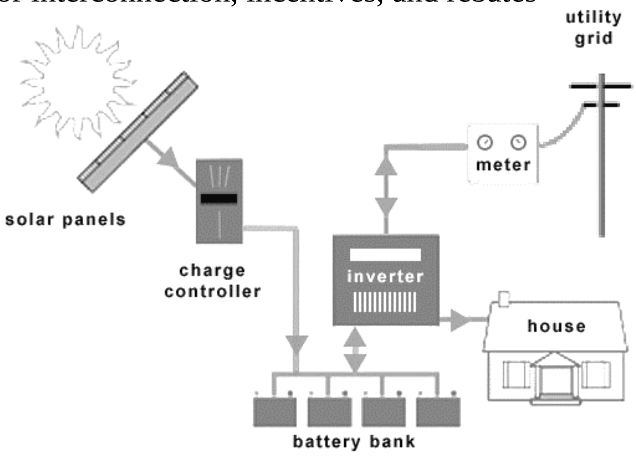


Fig. 26. Gird tied solar system with battery back up

Hybrid system

Hybrid system tries to combine multiple sources of power to maximize availability of power. It may source energy from sun, wind or diesel generator and back it up with battery.

- Multiple sources of generation allows for complementary sources and backup. For instance, when it is sunny out the PV array will charge the battery; if it is cloudy and windy, a wind turbine can charge the batteries.
- Array size and battery bank capacity can typically be reduced and not having to oversize for periods of no sun
- More complex system design and installation
- Multiple power sources can increase upfront expenses
- Wind turbines and generators require regular maintenance.

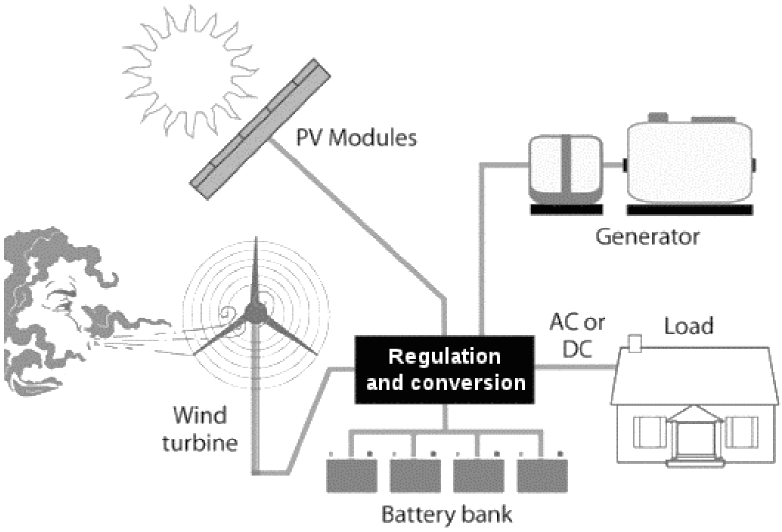


Fig. 27. Hybrid power systems

Types of Solar Cells

There are different types of photovoltaic cells available to buy, but mainly they are manufactured from silicon (Si). The use of silicon in the manufacture of photovoltaic cells produces the stereo typical uniform blue coloured PV cell which we see on roof tops and the sides of buildings.

The two major types of photovoltaic cell materials used are crystalline silicon and thin film deposits, which vary from each other in terms of light absorption efficiency, energy conversion efficiency, manufacturing technology and cost of production. Crystalline silicon PV cells are the most common type of photovoltaic cell in use today and are also one of the earliest successful PV devices.

The three general types of photovoltaic cells made from silicon are:

1. Mono-crystalline Silicon – also known as single-crystal silicon
2. Poly-crystalline Silicon – also known as multi-crystal silicon
3. Thin Film Silicon

Noor Complex is the world's largest concentrated solar power (CSP) plant, located in the Sahara Desert. The project has a 580-megawatt capacity.

Crystalline Silicon (c-Si)

This is the most common technology used to produce photovoltaic cells representing about 90% of the market today. Crystalline photovoltaic cells are made from silicon which is first melted, and then crystallised into ingots or casting’s of pure silicon. Thin slices of silicon called wafers, are cut from a single crystal of silicon (Mono-crystalline) or from a block of silicon crystals (Poly-crystalline) to make individual cells. The conversion efficiency for these types of photovoltaic cell ranges between 10% and 20%.

Mono-crystalline Silicon is a type of photovoltaic cell material manufactured from a single-crystal silicon structure which is uniform in shape because the entire structure is grown from the same crystal. High purity silicon is melted in a crucible. A single-crystal silicon seed is dipped into this molten silicon and is slowly pulled out from the liquid producing a single-crystal ingot. The ingot is then cut into very thin wafers or slices which are then polished, doped, coated, interconnected and assembled into modules and arrays. These types of photovoltaic cells are also widely used in photovoltaic panel construction.

Compared to non-crystalline cells, the uniform molecular structure of the silicon wafer makes it ideal for transferring loose electrons through the material resulting in a high energy conversion efficiency. The conversion efficiency for a mono-crystalline cell ranges between 15 to 20%.

Not only are they energy efficient, mono-crystalline photovoltaic cells are highly reliable for outdoor power applications due to their wafer thickness. However, to make an effective PV cell, the silicon has to be "doped" with other elements to make the required N-type and P-type conductive layers.

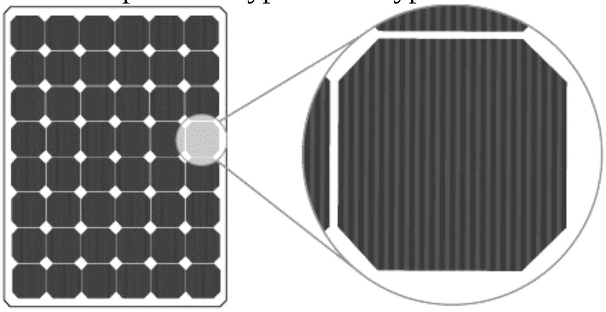


Fig. 28. Monocrystalline solar panels

Poly-crystalline Silicon also known as multi-crystalline silicon, is cast to produce a silicon ingot. The silicon molecular structure consists of several smaller groups or grains of crystals, which introduce boundaries between them. Poly-crystalline PV cells are less energy efficient than the previous mono-crystalline silicon PV cells because these boundaries restrict the flow of electrons through it by encouraging the negative electrons to recombine with the positive holes reducing the power output of the cell.

The result of this means that a poly-crystalline PV cell only has an energy conversion efficiency of between 10 to 14%. However, these types of photovoltaic cell are much less expensive to produce than the equivalent single mono-crystalline silicon due to their lower manufacturing costs.

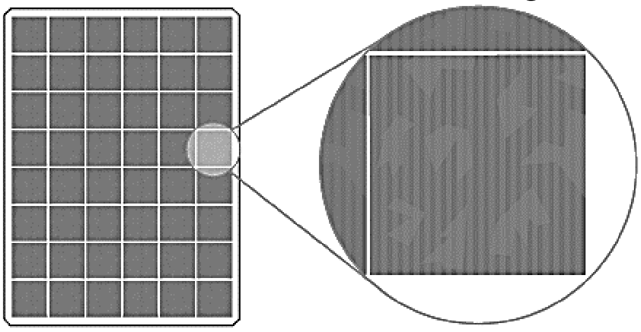


Fig. 29. Polycrystalline solar panels

Thin Film Solar Cell

Thin Film Solar Cells are another type of photovoltaic cell which were originally developed for space applications with a better power-to-size and weight ratio compared to the previous crystalline silicon devices. Thin film photovoltaics are produced by printing or spraying a thin semiconductor layer of PV material onto a glass, metal or plastic foil substrate. By applying these materials in thin layers, the overall thickness of each photovoltaic cell is substantially smaller than an equivalent cut crystalline cell, hence the name "thin film". As the PV materials used in these types of photovoltaic cells are sprayed directly onto a glass or metal substrate, the manufacturing process is therefore faster are cheaper making thin film PV technology more viable for use in a home solar system as their payback time is shorter.

However, although thin film materials have higher light absorption than equivalent crystalline materials, thin film PV cells suffer from poor cell conversion efficiency due to their non-single crystal structure, requiring larger sized cells. Semiconductor materials used for the thin film types of photovoltaic cell include: Cadmium Telluride, Amorphous Silicon and Copper Indium diSelenide or CIS.

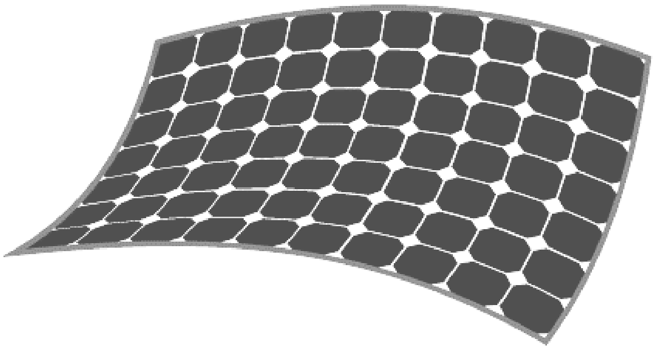


Fig. 30. Thinfilm solar panels

Cadmium Telluride, (CdTe) is a poly-crystalline semiconductor material made from cadmium and tellurium. Thin film cadmium telluride has a high light absorption level so the amount of CdTe required can be quite minimal with less than 1.0 microns of semiconductor material is needed to effectively absorb sunlight for the solar device to perform.

Although the process of spraying or printing the thin film is relatively easy making it cheap to manufacture these types of photovoltaic cell, the main material, cadmium is a toxic heavy metal can pollute the environment if the cell is damaged or broken. Another disadvantage of these types of photovoltaic cells is that the conversion efficiency for a cadmium telluride PV cell can be low at less than 10%.

Amorphous Silicon, (a-Si) is a non-crystalline form of silicon that is widely used in calculators, consumer electronics and solar garden products that require a small current at a low voltage. Of the different types of photovoltaic cell available, amorphous silicon has the highest light absorption of over 40 times higher than crystalline silicon. The advantage of this is that a much thinner layer of amorphous silicon material is required to make a thin film PV cell reducing manufacturing costs and price.

Amorphous silicon cells have various advantages and disadvantages. On the plus side, amorphous silicon can be deposited on a variety of low cost rigid and flexible substrates such as polymers, thin metals and plastics as well as tinted glass for building integration. However, on the minus side, two of the main disadvantages of amorphous silicon (a-Si) is its very low conversion efficiency ranging from between 7 to 9% when new, degrading down within a few months of exposure to sunlight to less than 5%.

Copper Indium diSelenide, (CIS) is another type of poly-crystalline semiconductor material composed of Copper, Indium and Selenium, (CuInSe2). Thin film CIS types of photovoltaic cell can produce conversion efficiencies of nearly 10%, almost double that of amorphous silicon without suffering from the same outdoor degradation problems due to their thicker film. Also CIS cells are one of the most light-absorbent semiconductor compounds absorbing up to 90% of the solar spectrum.

Although Copper Indium diSelenide, CIS cells are efficient, the complexity of the formulation of the semiconductor compound makes them difficult to manufacture and expensive. Also, Indium is a relatively expensive material due to its limited availability with manufacturing safety issues a concern as hydrogen selenide is an extremely toxic gas.

Copper Indium Gallium diSelenide, (CIGS) is another type of photovoltaic cell. It is basically a P-type poly-crystalline thin film material based on the previous copper indium diselenide (CIS) semiconductor material. The addition of small amounts of the compound Gallium (Ga) produces a photovoltaic cell with a higher conversion efficiency of around 12% from the same amount of sunlight with an open circuit voltage of about 0.7 volts. This is because Gallium, which is a liquid similar to mercury at room temperatures, increases the light-absorbing band gap of the cell, which matches more closely the solar spectrum, thereby improving its conductivity allowing electrons to freely move through the cell to the electrodes.

Other Types of Photovoltaic Cell

Apart from the commonly used types of photovoltaic cell mentioned above, and which account for about 95% of the commercial market, other types of photovoltaic cell currently being developed include:

Multijunction PV Cells – These are types of photovoltaic cell designed to maximise the overall conversion efficiency of the cell by creating a multi-layered design in which two or more PV junctions are layered one on top of the other. The cell is made up of various semiconductor materials in thin-film form for each individual layer.

The advantage of this is that each layer extracts energy from each photon from a particular portion of the light spectrum that is bombarding the cell. This layering of the PV materials increases the overall efficiency and reduces the degradation in efficiency that occurs with standard amorphous silicon cells.

Dye-Sensitive PV Cells – This type of technology is considered to be the 3rd generation of solar cells. Instead of using solid-state PN-junction technology to convert photon energy into electrical energy, an electrolyte, liquid, gel or solid is used to produce a photo-electrochemical PV cell. These types of photovoltaic cells are manufactured using microscopic molecules of photosensitive dye on a nano-crystalline or polymer film. The photon light energy being absorbed by the dye releases electrons into the conduction band causing a flow of the electricity through the semiconductor. The advantage of a dye-sensitive nano-crystalline photo-electrochemical photovoltaic cell is that the dye can be screen printed onto any surface producing conversion efficiencies of around 10%.

3D Photovoltaic Cells – This type of photovoltaic cell uses a unique three-dimensional structure to absorb the photon light energy from all directions and not just from the top as in convectional flat PV cells. The cell uses a 3D array of miniature molecular structures which capture as much sunlight as possible boosting its efficiency and voltage output while reducing its size, weight and complexity.

Solar panel type	Advantages	Disadvantages
Monocrystalline	• High efficiency/performance • Aesthetics	• Higher costs
Polycrystalline	• Low cost	• Lower efficiency/performance
Thin-film	• Portable and flexible • Lightweight • Aesthetics	• Lowest efficiency/performance

Table: Comparison of types of Solar cells

China is the world's largest manufacturer of solar panels.

PV Module I-V Characteristics

Solar Cell I-V Characteristic Curves show the current and voltage (I-V) characteristics of a particular photovoltaic (PV) cell, module or array giving a detailed description of its solar energy conversion ability and efficiency. Knowing the electrical I-V characteristics (more importantly P_{max}) of a solar cell, or panel is critical in determining the device's output performance and solar efficiency.

The main electrical characteristics of a PV cell or module are summarized in the relationship between the current and voltage produced on a typical solar cell I-V characteristics curve. The intensity of the solar radiation (insolation) that hits the cell controls the current (I), while the increases in the temperature of the solar cell reduces its voltage (V).

Solar cells produce direct current (DC) electricity and current times voltage equals power, so we can create solar cell I-V curves representing the current versus the voltage for a photovoltaic device.

Solar Cell I-V Characteristics Curves are basically a graphical representation of the operation of a solar cell or module summarising the relationship between the current and voltage at the existing conditions of irradiance and temperature. I-V curves provide the information required to configure a solar system so that it can operate as close to its optimal peak power point (MPP) as possible.

Solar Cell I-V Characteristic Curve

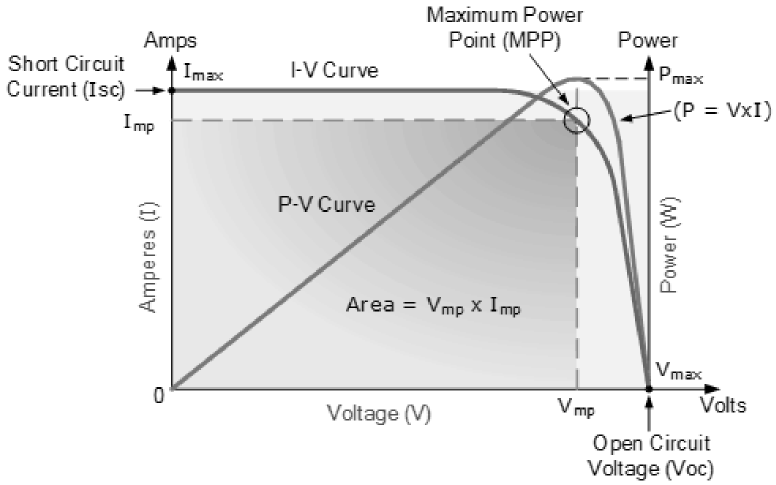


Fig. 31. Solar Cell I-V Characteristic Curve

The above graph shows the current-voltage (I-V) characteristics of a typical silicon PV cell operating under normal conditions. The power delivered by a solar cell is the product of current and voltage (I × V). If the multiplication is done, point for point, for all voltages from short-circuit to open-circuit conditions, the power curve above is obtained for a given radiation level.

With the solar cell open-circuited, that is not connected to any load, the current will be at its minimum (zero) and the voltage across the cell is at its maximum, known as the solar cells open circuit voltage, or V_{oc}. At the other extreme, when the solar cell is short circuited, that is the positive and negative leads connected together, the voltage across the cell is at its minimum (zero) but the current flowing out of the cell reaches its maximum, known as the solar cells short circuit current, or I_{sc}.

Then the span of the solar cell I-V characteristics curve ranges from the short circuit current (I_{sc}) at zero output volts, to zero current at the full open circuit voltage (V_{oc}). In other words, the maximum voltage available from a cell is at open circuit, and the maximum current at closed circuit. Of course, neither of these two conditions generates any electrical power, but there must be a point somewhere in between were the solar cell generates maximum power.

However, there is one particular combination of current and voltage for which the power reaches its maximum value, at Imp and V_{mp}. In other words, the point at which the cell generates maximum electrical power and this is shown at the top right area of the green rectangle. This is the “maximum power point” or MPP. Therefore the ideal operation of a photovoltaic cell (or panel) is defined to be at the maximum power point.

The maximum power point (MPP) of a solar cell is positioned near the bend in the I-V characteristics curve. The corresponding values of Vmp and Imp can be estimated from the open circuit voltage and the short circuit current: $V_{mp} \cong (0.8–0.90)V_{oc}$ and $I_{mp} \cong (0.85–0.95)I_{sc}$. Since solar cell output voltage and current both depend on temperature, the actual output power will vary with changes in ambient temperature.

Solar Panel I-V Characteristic Curves

Photovoltaic panels can be wired or connected together in either series or parallel combinations, or both to increase the voltage or current capacity of the solar array. If the array panels are connected together in a series combination, then the voltage increases and if connected together in parallel then the current increases. The electrical power in Watts, generated by these different photovoltaic combinations will still be the product of the voltage times the current, (P = V × I). However the solar panels are connected together, the upper right hand corner will always be the maximum power point (MPP) of the array.

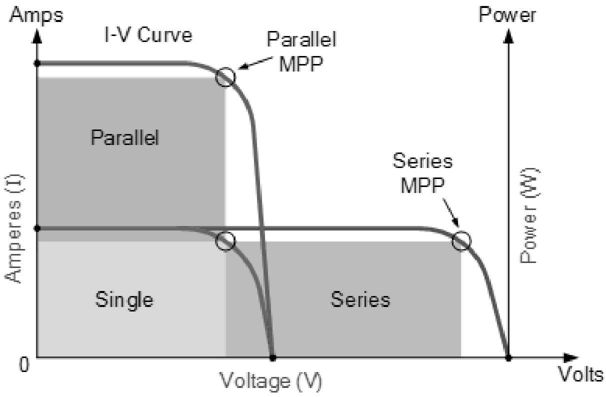


Fig. 32. Solar Panel I-V Characteristic Curves

The Electrical Characteristics of a Photovoltaic Array

The electrical characteristics of a photovoltaic array are summarised in the relationship between the output current and voltage. The amount and intensity of solar insolation (solar irradiance) controls the amount of output current (I), and the operating temperature of the solar cells affects the output voltage (V) of the PV array. Solar cell I-V characteristic curves that summarise the relationship between the current and voltage are generally provided by the panels manufacturer and are given as:

Solar Array Parameters

- V_{OC} = open-circuit voltage: – This is the maximum voltage that the array provides when the terminals are not connected to any load (an open circuit condition). This value is much higher than V_{mp} which relates to the operation of the PV array which is fixed by the load. This value depends upon the number of PV panels connected together in series.
- I_{SC} = short-circuit current – The maximum current provided by the PV array when the output connectors are shorted together (a short circuit condition). This value is much higher than I_{mp} which relates to the normal operating circuit current.
- MPP = maximum power point – This relates to the point where the power supplied by the array that is connected to the load (batteries, inverters) is at its maximum value, where MPP = $I_{mp} \times V_{mp}$. The maximum power point of a photovoltaic array is measured in Watts (W) or peak Watts (Wp).
- FF = fill factor – The fill factor is the relationship between the maximum power that the array can actually provide under normal operating conditions and the product of the open-circuit voltage times the short-circuit current, ($V_{oc} \times I_{sc}$) This fill factor value gives an idea of the quality of the array and the closer the fill factor is to 1 (unity), the more power the array can provide. Typical values are between 0.7 and 0.8.
- % eff = percent efficiency – The efficiency of a photovoltaic array is the ratio between the maximum electrical power that the array can produce compared to the amount of solar irradiance hitting the array. The efficiency of a typical solar array is normally low at around 10-12%, depending on the type of cells (monocrystalline, polycrystalline, amorphous or thin film) being used.

Photovoltaic I-V characteristics curves provide the information needed for us to configure a solar power array so that it can operate as close as possible to its maximum peak power point. The peak power point is measured as the PV module produces its maximum amount of power when exposed to solar radiation equivalent to 1000 watts per square metre, 1000 W/m^2 or $1kW/m^2$.

Efficiency & Quality of the Cell

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell. Therefore, conditions under which efficiency is measured must be carefully controlled in order to compare the performance of one device to another. Terrestrial solar cells are measured under AM1.5 conditions and at a temperature of 25°C. Solar cells intended for space use are measured under AM0 conditions.

The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

$$P_{max} = V_{OC}\ I_{SC}\ FF$$

$$\eta = \frac{V_{OC} I_{SC} FF}{P_{in}}$$

Where, V_{oc} is the open-circuit voltage;
I_{sc} is the short-circuit current;
FF is the fill factor and
η is the efficiency.

Factors affecting conversion efficiency

- **Wavelength:** The sunlight that reaches the earth's surface has wavelengths from ultraviolet, through the visible range, to infrared. When light strikes the surface of a solar cell, some photons are reflected, while others pass right through. Some of the absorbed photons have their energy turned into heat. The remainder have the right amount of energy to separate electrons from their atomic bonds to produce charge carriers and electric current.
- **Recombination:** It is one of the fundamental factors that limits efficiency. Indirect recombination is a process in which the electrons or holes encounter an impurity, a defect in the crystal structure, or interface that makes it easier for them to recombine and release their energy as heat.
- **Temperature:** Solar cells generally work best at low temperatures. Higher temperatures cause the semiconductor properties to shift, resulting in a slight increase in current, but a much larger decrease in voltage. Extreme increases in temperature can also damage the cell and other module materials, leading to shorter operating lifetimes.
- **Reflection:** A cell's efficiency can be increased by minimizing the amount of light reflected away from the cell's surface. For example, untreated silicon reflects more than 30% of incident light. Anti-reflection coatings and textured surfaces help decrease reflection. A high-efficiency cell will appear dark blue or black.

Quality of solar cell

The Fill Factor (FF) is essentially a measure of quality of the solar cell. It is calculated by comparing the maximum power to the theoretical power that would be output at both the open circuit voltage and short circuit current together. The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. A larger fill factor is desirable, and corresponds to an I-V sweep that is more square-like. Typical fill factors range from 0.5 to 0.82.

Most solar panels are between 15% and 20% efficient, with outliers on either side of the range. High-quality solar panels can exceed 22% efficiency in some cases (and almost reach 23%), but the majority of photovoltaic panels available are not above 20% efficiency.

Increasing efficiency of solar cell

There are ways to improve the efficiency of PV cells, all of which come with an increased cost.

- One way is to decrease the number of semiconductor impurities and crystal structure deformations. This can be achieved through the production of monocrystalline, or "single-crystal" cells. A more pure and uniform cell has a higher chance of interacting with incoming photons.
- Another method is to use a more efficient semiconducting material such as Gallium Arsenide. Although it's much more rare and expensive than silicon, gallium arsenide has an optimal band-gap of 1.4 electron volts, allowing for a higher percentage of the Sun's energy to be harnessed.
- Multiple layers of semiconductor material called p-n junctions can also be used to increase cell efficiency. These multi-junction cells harness energy from multiple sections of the solar spectrum as each junction has a different band gap energy.

- Efficiency can also be increased through concentrated photovoltaics. This method involves concentrating the Sun's energy through various methods to increase the intensity of energy hitting the solar cell.

Regulations for quality

The manufacture of photovoltaic modules is governed by several standards required by the IEC (International Electrotechnical Commission) in order to be marketed on the international market.

These standards are as follows:

- The standard IEC 61215 (crystalline) or IEC 61646 (amorph) certifies a guarantee of quality in terms of respect for electrical parameters and mechanical stability. The requirements of this standard refer to the qualification of the design and approval of photovoltaic modules for land application and for long-term use.
- The standard IEC 61730 specifically addresses the topics of prevention against electric shock, fire hazard and bodily injury due to mechanical and environmental constraints.
- This standard, whose specificities concern the safety aspects of the modules, complements the IEC 61215 standard, which fixes the electrical performance.

At the end of May 2019, the cumulative solar power capacity of Germany reached 47.72 GW.

Series and parallel connections

Depending on the equipment that the system uses and the size of the system, your solar installer may decide to wire your solar panels in series, in parallel, or in a combination of the two. Here are the fundamental differences between wiring solar panels in series vs. in parallel:

Wiring solar panels in series

When a solar installer wires your solar panels in a series, each panel is connected to the next in a “string.” The total voltage of each solar panel is summed together, but the amps of electrical current stay the same. When you wire in series, there is just a single wire leading from the roof for each string of solar panels.

Wiring solar panels in parallel

When an installer wires your solar panels in parallel, each panel’s wires are connected to a centralized wire leading from the roof. The amps of electrical current for each solar panel are summed together, but the system voltage stays the same. Wiring your solar panels in parallel results in more wires running from your solar panel system.

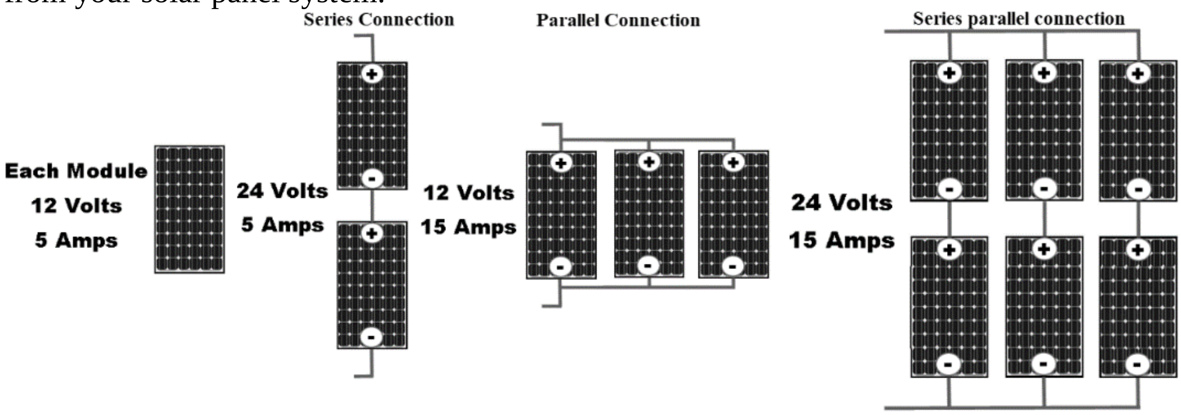


Fig. 33. Series, parallel Series parallel connections

In theory, parallel wiring is a better option for many electrical applications because it allows for continuous operation of the panels that are not malfunctioning. But, it is not always the best choice for all applications. When designing your solar system, your installer might decide that series wiring is better suited for your application or he might choose a hybrid approach by series wiring some panels and parallel wiring others.

Maximum power point tracking

MPPT or Maximum Power Point Tracking is an algorithm that is included in charge controllers used for extracting maximum available power from PV module under certain conditions. The voltage at which

PV module can produce maximum power is called maximum power point (or peak power voltage). Maximum power varies with solar radiation, ambient temperature and solar cell temperature.

Typical PV module produces power with maximum power voltage of around 17 V when measured at a cell temperature of 25°C, it can drop to around 15 V on a very hot day and it can also rise to 18 V on a very cold day.

The major principle of MPPT is to extract the maximum available power from PV module by making them operate at the most efficient voltage (maximum power point). MPPT checks output of PV module, compares it to battery voltage then fixes what is the best power that PV module can produce to charge the battery and converts it to the best voltage to get maximum current into battery. It can also supply power to a DC load, which is connected directly to the battery.

MPPT is most effective under these conditions:

- Cold weather, cloudy or hazy days: Normally, PV module works better at cold temperatures and MPPT is utilized to extract maximum power available from them.
- When battery is deeply discharged: MPPT can extract more current and charge the battery if the state of charge in the battery is lowers.

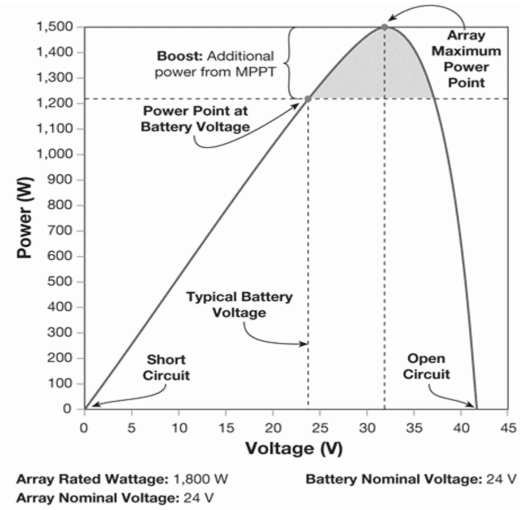


Fig.34. Comparison of MPPT Vs Non MPPT IV Curve

Example: MPPT On a Cold Winter Day

- If the outside temperature is 20°F (-7°C) and the wind is blowing a bit, the PV cell temperature rises to only around 32°F (0°C). The Vpp = 18V. Batteries are a bit low, and loads are on, so the battery voltage = 12.0.
- The ratio of Vpp to battery voltage is 18:12 = 1.5:1.
- Under these conditions, a theoretically perfect MPPT (with no voltage drop in the array circuit) would deliver a 50% increase in charge current. In reality, there are losses in the conversion just as there is friction in a car’s transmission. Reports from the field indicate that increases of 20 to 30% are typically observed.

MPPT solar charge controller

- A MPPT solar charge controller is the charge controller embedded with MPPT algorithm to maximize the amount of current going into the battery from PV module.
- MPPT is DC to DC converter which operates by taking DC input from PV module, changing it to AC and converting it back to a different DC voltage and current to exactly match the PV module to the battery.

Smart Grids can integrate solar sourced electricity such as Rooftop solar PV along with traditional power generation allowing higher flexibility to have localized and right sized power plants with reduced transmission loss, zero environmental concerns and higher efficiency.

Examples of DC to DC converter are

- Boost converter is power converter which DC input voltage is less than DC output voltage. That means PV input voltage is less than the battery voltage in system.

- Buck converter is power converter which DC input voltage is greater than DC output voltage. That means PV input voltage is greater than the battery voltage in system.
- MPPT algorithm can be applied to both of them depending on system design. Normally, for battery system voltage is equal or less than 48 V, buck converter is useful. On the other hand, if battery system voltage is greater than 48 V, boost converter should be chosen.
- MPPT solar charge controllers are useful for off-grid solar power systems such as stand-alone solar power system, solar home system and solar water pump system, etc.

Main features of MPPT solar charge controller

- In any applications which PV module is energy source, MPPT solar charge controller is used to correct for detecting the variations in the current-voltage characteristics of solar cell and shown by I-V curve.
- MPPT solar charge controller is necessary for any solar power systems need to extract maximum power from PV module; it forces PV module to operate at voltage close to maximum power point to draw maximum available power.
- MPPT solar charge controller allows users to use PV module with a higher voltage output than operating voltage of battery system.
- For example, if PV module has to be placed far away from charge controller and battery, its wire size must be very large to reduce voltage drop. With a MPPT solar charge controller, users can wire PV module for 24 or 48 V (depending on charge controller and PV modules) and bring power into 12 or 24 V battery system. This means it reduces the wire size needed while retaining full output of PV module.
- MPPT solar charge controller reduces complexity of system while output of system is high efficiency. Additionally, it can be applied to use with more energy sources. Since PV output power is used to control DC-DC converter directly.
- MPPT solar charge controller can be applied to other renewable energy sources such as small water turbines, wind-power turbines, etc.

Conditions That Limits the Effectiveness of MPPT

The V_{mp} of a solar module decreases as the temperature of the module increases. In very hot weather, the V_{mp} may be close or even less than battery voltage. In this situation, there will be very little or no MPPT gain compared to traditional controllers. However, systems with modules of higher nominal voltage than the battery bank will always have an array V_{mp} greater than battery voltage. Additionally, the savings in wiring due to reduced solar current make MPPT worthwhile even in hot climates.

Applications.

- **Residential Application:** Use of solar energy for homes has number of advantages. The solar energy is used in residential homes for heating the water with the help of solar heater. The photovoltaic cell installed on the roof of the house collects the solar energy and is used to warm the water. Solar energy can also be used to generate electricity. Batteries store energy captured in day time and supply power throughout the day. The use of solar appliances is one of the best ways to cut the expenditure on energy.
- **Industrial Application:** Sun’s thermal energy is used in office, warehouse and industry to supply power. Solar energy is used to power radio and TV stations. It is also used to supply power to lighthouse and warning light for aircraft.
- **Remote Application:** Solar energy can be used for power generation in remotely situated places like schools, homes, clinics and buildings. Water pumps run on solar energy in remote areas. Large scale desalination plant also use power generated from solar energy instead of electricity.
- **Transportation:** Solar energy is also used for public transportation such as trolleys, buses and light-rails.
- **Pool heating:** Solar heating system can be used to heat up water in pool during cold seasons.

- **Solar Green Houses:** A green house is a structure covered with transparent material (glass or plastic) that acts as a solar collector and utilises solar radiant energy to grow plants. It has heating, cooling and ventilating devices for controlling the temperature inside the green house.
- **Solar Cooking:** The solar cooker requires neither fuel nor attention while cooking food and there is no pollution, no charring or overflowing of food and the most important advantage is that nutritional value of the cooked food is very high as the vita-mins and natural tastes of the food are not destroyed.
- **Solar furnace:** In a Solar furnace, high temperature is obtained by concentrating the solar radiations onto a specimen using a number of heliostats (turn-able mirrors) ar-ranged on a sloping surface.
- **Solar Drying of Agricultural and Animal Products:** Solar drying, especially of fruits improves fruit quality as the sugar concentra-tion increases on drying. Other agricultural products commonly solar-dried are potato-chips, berseem, grains of maize and paddy, ginger, peas, pepper, cashew-nuts, timber drying and tobacco curing. Spray drying of milk and fish drying are examples of solar dried animal products.
- **Solar-pumping:** In solar pumping, the power generated by solar-energy is utilized for pumping water for irrigation purposes.
- **Solar-distillation:** In arid semi and or coastal areas there is scarcity of potable water. The abundant sunlight in these areas can be used for converting saline water into portable distilled water by the method of solar distillation.