SOLAR ENERGY

Solar collector

A solar collector is a device that collects and/or concentrates solar radiation from the Sun, converts it into heat and transfer this heat to a fluid (usually water, air or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the hot water or space conditioning equipment or to a thermal energy storage tank from which it can be drawn for use at night and/or cloudy days.

Solar collectors are of two types – i) Non-concentrating collector (flat plate collector)
ii) Concentrating collector

A **Flat Plate Collector** is a heat exchanger that converts the radiant solar energy from the sun into heat energy using the greenhouse effect. It collects, or captures, solar energy and uses that energy to heat water in the home for bathing, washing and heating, and can even be used to heat outdoor swimming pools and hot tubs.

For most residential and small commercial hot water applications, the *solar flat plate collector* tends to be more cost effective due to their simple design, low cost, and relatively easier installation compared to other forms of hot water heating systems. Also, solar flat plate collectors are more than capable of delivering the necessary quantity of hot water at the required temperature.

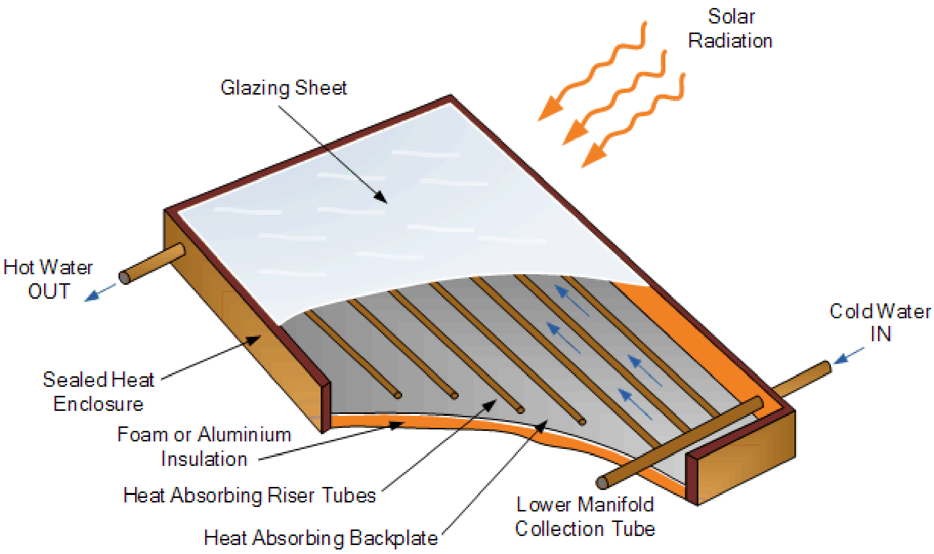
Solar Flat Plate Collector on Roof

A solar flat plate collector typically consists of a large heat absorbing plate, usually a large sheet of copper or aluminium as they are both good conductors of heat, which is painted or chemically etched black to absorb as much solar radiation as possible for maximum efficiency. This blackened heat absorbing surface has several parallel copper pipes or tubes called risers, running length ways across the plate which contain the heat transfer fluid, typically water.

These copper pipes are bonded, soldered or brazed directly to the absorber plate to ensure maximum surface contact and heat transfer. Sunlight heats the absorbing surface which increases in temperature. As the plate gets hotter this heat is conducted through the risers and absorbed by the fluid flowing inside the copper pipes which is then used by the household.

The pipes and absorber plate are enclosed in an insulated metal or wooden box with a sheet of glazing material, either glass or plastic on the front to protect the enclosed absorber plate and create an insulating air space. This glazing material does not absorb the suns thermal energy to any significant extent and therefore most of the incoming radiation is received by the blackened absorber.

The air gap between the plate and glazing material traps this heat preventing it from escaping back into the atmosphere. As the absorber plate warms up, it transfers heat to the fluid within the collector but it also loses heat to its surroundings. To minimize this loss of heat, the bottom and sides of a flat plate collector are insulated with high temperature rigid foam or aluminium foil insulation as shown.



Typical Flat Plate Collector

Flat plate collectors can heat the fluid inside using either direct or indirect sunlight from a wide range of different angles. They also function in diffused light, which is dominant on cloudy days as it is the surrounding heat that is being absorbed and not the light, unlike photovoltaic cells. How hot the circulating water gets will depend mostly on the time of the year, how clear the skies are and how slowly the water flows through the collector's pipes.

A **concentrating solar collector** is a solar collector that uses reflective surfaces to concentrate sunlight onto a small area, where it is absorbed and converted to heat or, in the case of solar photovoltaic (PV) devices, into electricity. Concentrators can increase the power flux of sunlight hundreds of times. This class of collector is used for high-temperature applications such as steam production for the generation of electricity and thermal detoxification. Concentrating collectors are best suited to climates that have a high percentage of clear sky days. The concentrating collectors are of following types :

i) Parabolic Dish Collectors
ii) Parabolic Trough Collectors
iii) Power Tower
iv) Stationary Concentrating Collector
v) Fresnel Reflectors

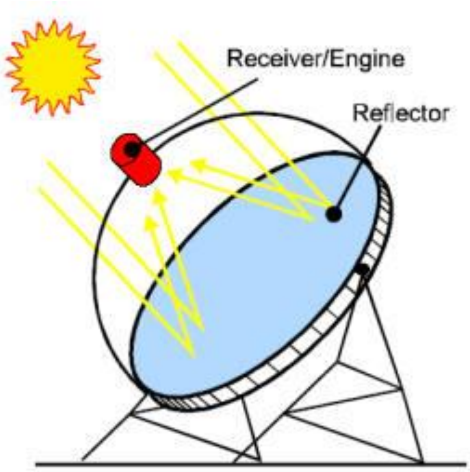
Parabolic Dish Collector

A Parabolic dish Collector consists of a parabolic-shaped point focus concentrator in the form of a dish that reflects solar radiation onto a receiver (absorber) mounted at the focal point. These concentrators are mounted on a structure with a two-axis tracking system to follow the sun.

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.

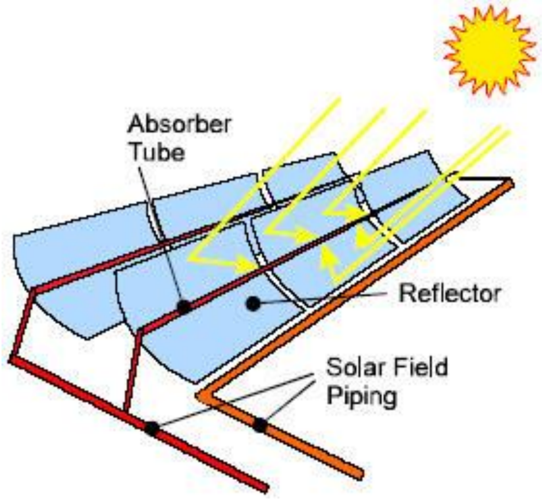
A typical parabolic dish collector has a dish of 6 m diameter. It can yield temperatures up to 3000°C.

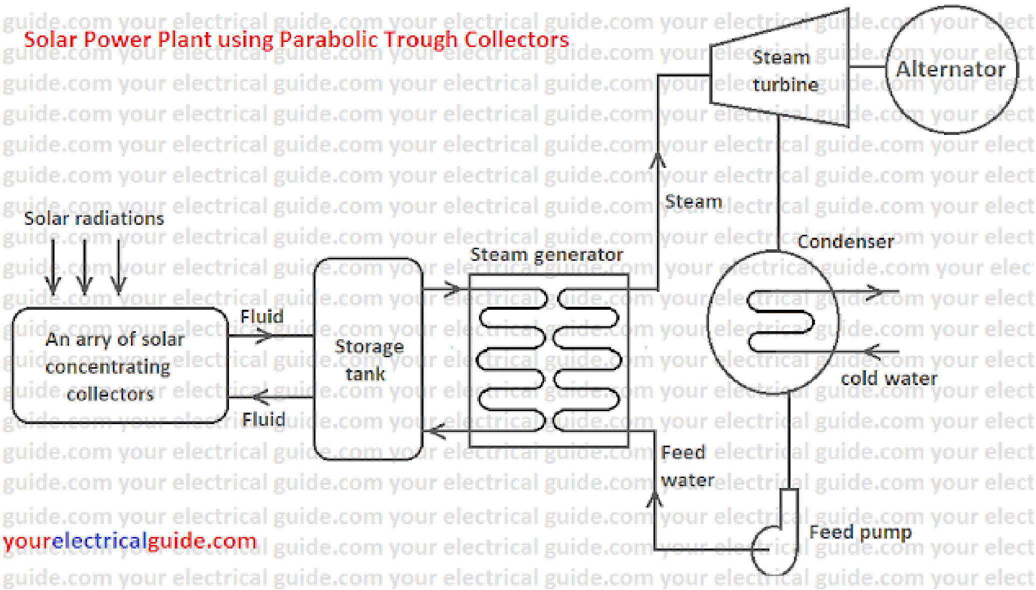
Due to the limitations of size and the small quantity of fluid, dish type solar collectors are suitable for only small power generation (up to few kW).



Parabolic Trough Collector

A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line. The receiver is a tube positioned directly above the middle of the parabolic mirror and filled with a working fluid. The reflector follows the sun during the daylight hours by tracking along a single axis. A working fluid (usually thermal oil or water or molten salt) is heated to 150–350 °C (302–662 °F) as it flows through the receiver and then the heat is transferred to water for producing steam for power generation. Trough systems are the most developed CSP technology.

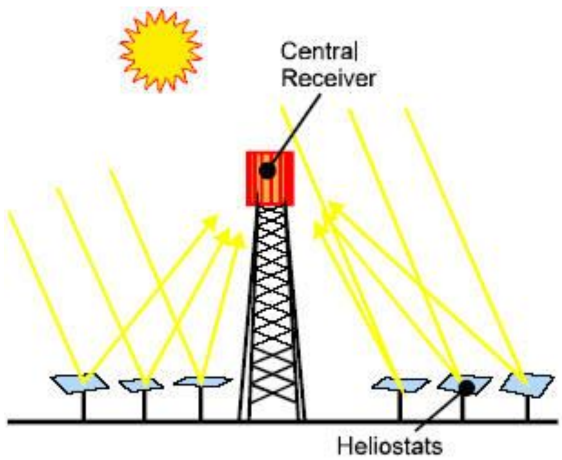


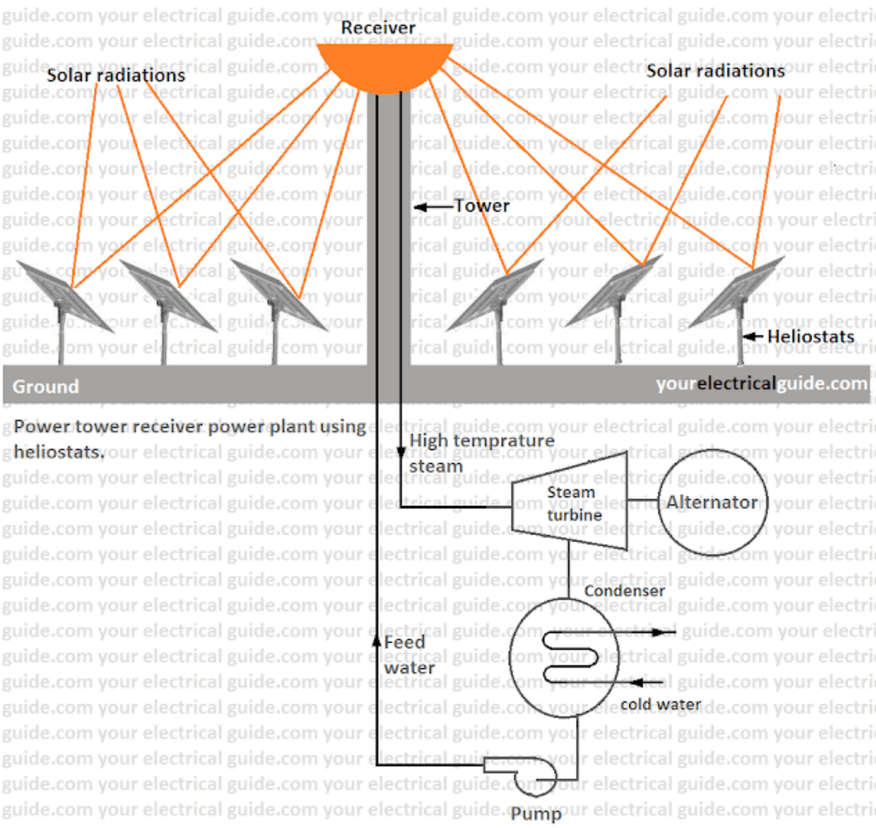


Power Tower System

Power tower or central receiver systems utilize a large number of independently-moving flat mirrors (heliostats) spread over a large area of ground to focus the reflected solar radiations onto a receiver mounted on the top of a tower of about 500 m height. The heliostats are installed all around the central tower. Each heliostat is rotated into two directions so as to track the sun.

The tower supports a bundle of vertical tubes containing the working fluid. The working fluid is heated in the receiver up to around 600°C is used to generate steam, which, in turn, is used in a conventional turbine-generator to produce electricity.

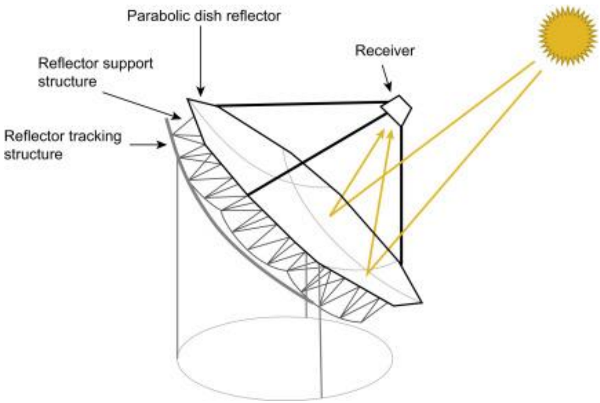




Power tower receiver power plant using heliostats.

Stationary Concentrating Collector

A stationary concentrating collector is a type of concentrating collector that uses compound parabolic reflectors and flat reflectors for directing solar energy to an accompanying absorber or aperture through a wide acceptance angle. The wide acceptance angle for these reflectors eliminates the need for a sun tracker. This class of collector includes parabolic trough flat-plate collectors, flat-plate collectors with parabolic boosting reflectors, and solar cookers. Development of the first two collectors has been done in Sweden. Solar cookers are used throughout the world, especially in the developing countries.



Fresnel Reflectors

Fresnel reflectors contain many thin, flat mirror strips to concentrate sunlight on tubes through which working fluid is pumped. Flat mirrors accommodate more reflective surfaces in the same amount of space than a parabolic reflector. They capture more available sunlight and also much cheaper than parabolic reflectors. Fresnel reflectors can be used in various sizes of CSPs. Fresnel reflectors are often said to be a technology with the lowest output than other methods.

Some new models of Fresnel reflectors with ray tracing capacity have recently been tested and initially proved to provide higher output than the standard version.

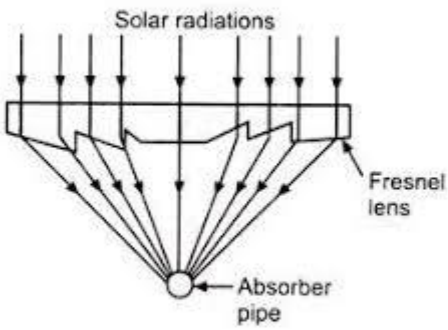


Fig. 3.7. Fresnel lens collector.

Comparison Between Flat Plate collector and concentrating type collector

Sl. No.	Flat Plate Collector	Concentrating Type Collector
1.	Absorber area is large.	Absorber area is small.
2.	Concentration ratio is 1.	Concentration ratio is high.
3.	An additional anti-freeze is used for protection.	No additional requirement is there.
4.	Design is easy.	Complex design.
5.	It has low insulation intensity.	It has high insulation intensity.
6.	This can reach only to a low-temperature range.	This can reach to a high-temperature range.
7.	Maximum Temperature of fluid is 300°C.	Fluid temperatures up to around 5000°C can be achieved.
8.	It uses both beam and diffuse radiation.	It is uses mainly beam radiation.
9.	Application limited to low temperature uses such as water heating and suitable for all places as it can work in clear and cloudy days.	High temperature application such as power generation and suitable where there are more clear days in a year.
10.	It is less efficient solar collector	It is the most powerful type of collector.
11.	Simple in maintenance.	Difficult in maintenance.
12.	This is comparatively low cost.	This is costly.

Solar Water Heating System & Its Working Principle

One of the popular devices that utilizes the solar energy is Solar Water Heating System (SWHS).

Solar Water Heating System Salient Features:

- Fuel Saving- A 100 litres capacity SWH can replace an electric geyser for residential use and saves 1500 units of electricity annually.
- Beneficial for Environment- A SWH of 100 litres capacity can prevent emission of 1.5 tonnes of carbon dioxide per year.
- Total Life- 15 to 20 years approximately.
- Costing- Rs.15000- 20,000 for a 100 litres capacity system and Rs.110-150 per installed litre for higher capacity systems.
- Payback period- 3-4 years when electricity is replaced 4-5 years when furnace oil is replaced 5-6 years when coal is replaced.

Major Components:

- Solar Collector, Its purpose is to collect solar energy
- Insulated Tank, Its purpose is to store hot water
- Supporting Stand
- Connecting Pipes and Instrumentation, etc.

Working Principle of SWH:

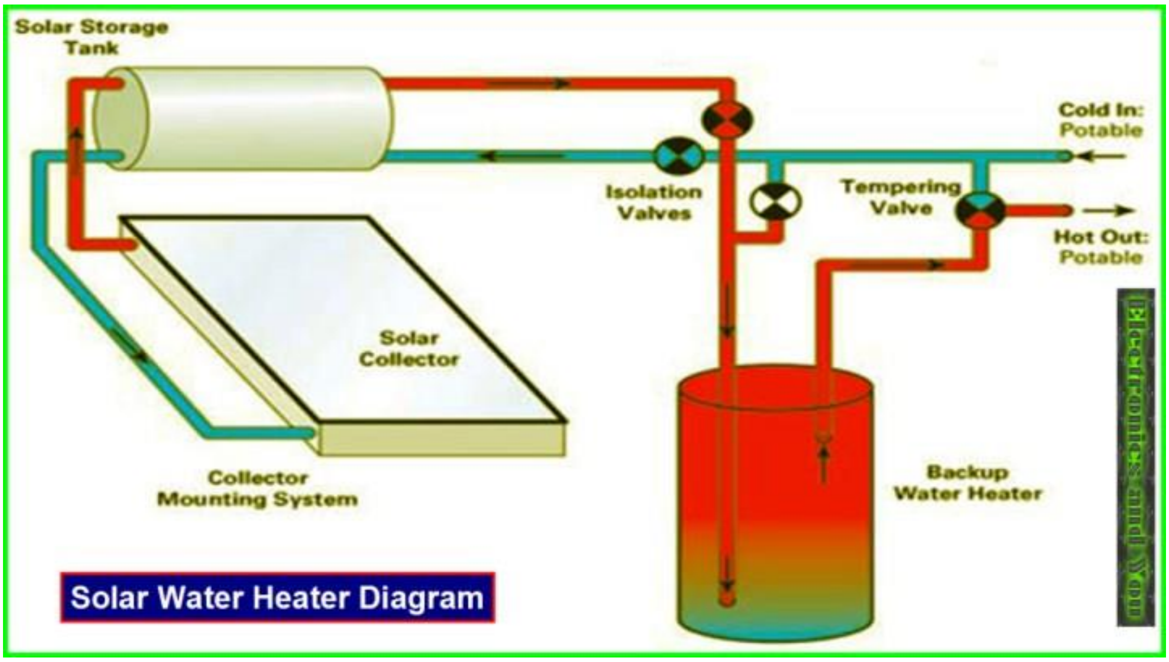
The Sun rays fall on the Solar Collector. A black absorbing surface (absorber) inside the collector, which absorbs solar radiation and transfers the heat energy to water flowing through it. Heated water is collected in a tank which is insulated to prevent heat loss. Then Circulation of water from the tank through the collector and back to the tank continues automatically.

A Solar Water Heater consists of a Collector panel to collect solar energy and an Insulated Storage Tank to store hot water.

Figure 1 Solar Water Heater

Applications:

- Water heating is one of the major uses of solar energy. It is implemented for providing hot water for showers, dishwashers, clothes washers etc.
- Solar Water Heating System (SWHS) can be used for Homes, Community Centres, Hospitals, Nursing Homes, Hotels, Dairy Plants, Swimming Pools, Canteens, Ashrams, Hostels, Industry etc.



Advantages of SWHS

- Use of Solar Water Heater (SWH) can reduce electricity or fuel bills considerably.
- Among all the solar energy devices available in the market, Solar Water Heater is found to be one of the most reliable and durable.
- Solar Water Heater has longest warranty period of all other solar energy devices.
- Solar Water Heater is known to has the fastest repayment of investment.

Solar thermal power plants

Solar thermal power plants are electricity generation plants that utilize energy from the Sun to heat a fluid to a high temperature. This fluid then transfers its heat to water, which then becomes superheated steam. This steam is then used to turn turbines in a power plant, and this mechanical energy is converted into electricity by a generator. This type of generation is essentially the same as electricity generation that uses fossil fuels, but generates steam using sunlight instead of combustion of fossil fuels. These systems use solar collectors to concentrate the Sun's rays on one point to achieve appropriately high temperatures.

There are two types of systems to collect solar radiation and store it - passive systems and active systems. Solar thermal power plants are considered active systems. These plants are designed to operate using only solar energy, but most plants can use fossil fuel combustion to supplement output when needed.

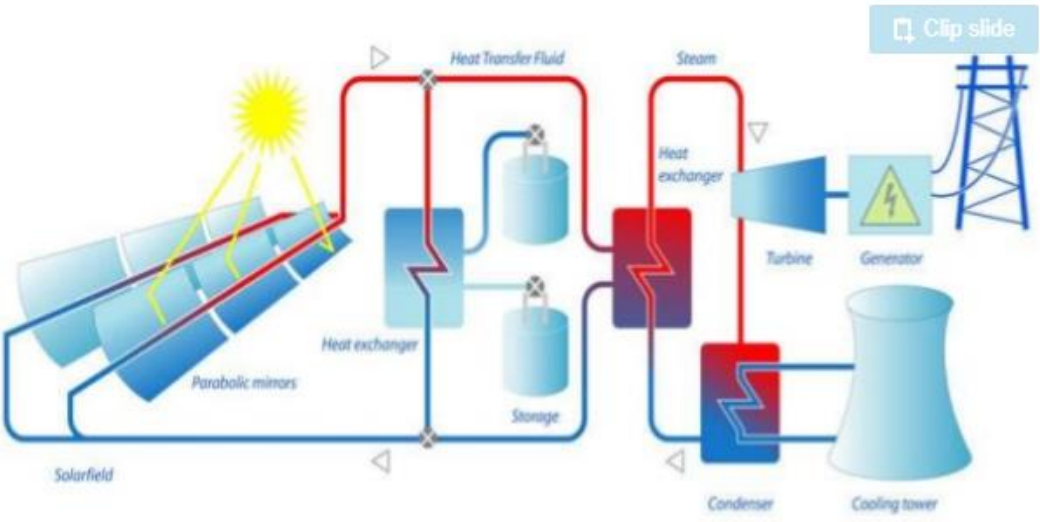
There are following types of solar thermal power plants:

1. Parabolic Trough System

These troughs, also known as line focus collectors, are composed of a long, parabolic shaped reflector that concentrates incident sunlight on a pipe that runs down the trough. The collectors sometimes utilize a single-axis Solar tracking system to track the Sun across the sky as it moves from east to west to ensure that there is always maximum solar energy incident on the mirrors. The receiver pipe in the center can reach temperatures upward of 400°C as the trough focuses Sun at 30-100 times its normal intensity.

Parabolic Trough Collectors

These troughs are lined up in rows on a solar field. A heat transfer fluid is heated as it is run through the pipes in the parabolic trough. This fluid then returns to heat exchangers at a central location where the heat is transferred to water, generating high-pressure superheated steam. This steam then moves a turbine to power a generator and produce electricity. The heat transfer fluid is then cooled and run back through the solar field.



Parabolic Trough System

2. Parabolic Dish System

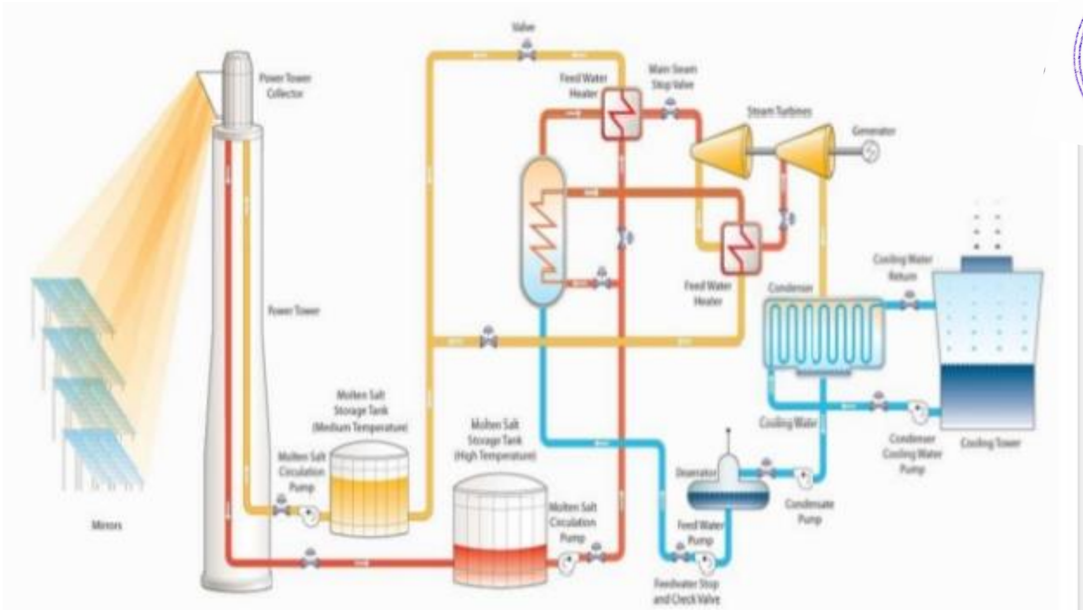
These are large parabolic dishes that use motors to track the Sun. This ensures that they always receive the highest possible amount of incoming solar radiation that they then concentrate at the focal point of the dish. These dishes can concentrate sunlight much better than parabolic troughs and the fluid run through them can reach temperatures upwards of 750°C. In these systems, a Stirling engine coverts heat to mechanical energy by compressing working fluid when cold and allowing the heated fluid to expand outward in a piston or move through a turbine. A generator then converts this mechanical energy to electricity.
Solar Towers

Parabolic Dish Collector

3. Solar Power Tower

Solar power towers are large towers that act as a central receiver for solar energy. They stand in the middle of a large array of mirrors that all concentrate sunlight on a point in the tower. These large number of flat, sun tracking mirrors are known as heliostats. In the tower, there is a mounted heat exchanger where the heat exchange fluid is warmed. The heat concentrated to this point can be 1500 times as intense as incident sunlight. The hot fluid is then used to create steam to run a turbine and generator, producing electricity. One drawback with these towers is they must be very large to be economical.

Solar Power Tower



Solar Power Tower System

4. Solar Pond

This is a pool of saltwater which collects and stores solar thermal energy. It uses so-called salinity-gradient technology. Basically, the bottom layer of the pond is extremely hot – up to 85 degrees Celsius – and acts as a transparent insulator, permitting sunlight to be trapped from which heat may be withdrawn or stored for later use. This technology has been used in Israel since 1984 to produce electricity.

Benefits and Drawbacks of Solar thermal power plants

- Because these systems can generate steam of such high temperatures, the conversion of heat energy to electricity is more efficient. As well, these plants get around the issue of being unable to efficiently store electricity by being able to store heat instead. The storage of heat is more efficient and cost-effective than storing electricity.
- Additionally, these plants can produce dispatchable baseload energy, which is important as it means these plants produce a reliable amount of energy and can be turned on or up at will, meeting the energy demands of society.
- In addition to this, solar thermal power plants represent a type of electricity generation technology that is cleaner than generating electricity by using fossil fuels. Thus, these are some of the cleanest options for generating electricity.
- Despite this, there are still associated environmental effects of these plants as a full life cycle analysis can show all associated carbon dioxide emissions involved in the building of these plants. However, emissions are still much lower than those associated with fossil fuel plants.
- Some of the drawbacks include the large amount of land necessary for these plants to operate efficiently. As well, the water demand of these plants can also be seen as an issue, as the production of enough steam requires large volumes of water.
- A final potential impact of the use of large focusing mirrors is the harmful effect these plants have on birds. Birds that fly in the way of the focused rays of Sun can be incinerated. Some reports of bird deaths at power plants such as these amount the deaths to about one bird every two minutes.[9]

Photovoltaic Cell

A photovoltaic (PV) cell, also known as a solar cell, is an electronic component that generates electricity when exposed to photons, or particles of light. This conversion is called the photovoltaic effect. There are several different types of PV cells which all use semiconductors to interact with incoming photons from the Sun in order to generate an electric current.

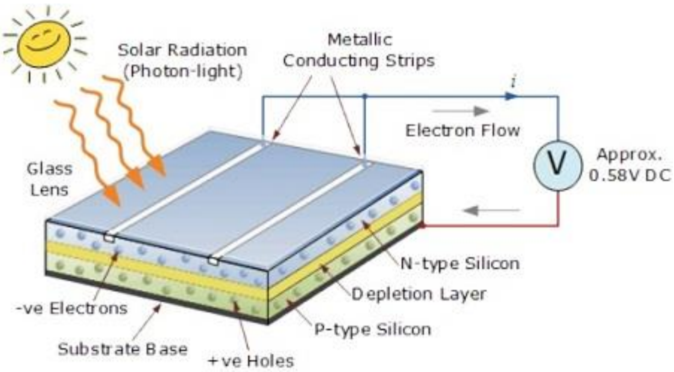
Principle of operation

Atoms of silicon crystal have four electrons in their outermost orbits and are stable by sharing four electrons from other neighbouring atoms. To make solar cell, silicon crystal is doped with impurity atoms. When a pentavalent impurity such as phosphorus is added to silicon, the four valence electrons of each pentavalent phosphorous atom are shared with four neighbouring silicon atoms through covalent bonds, and the fifth valence electron does not get any chance to create a covalent bond. This electron floats around the doped crystal as free electron and makes it negatively charged. This makes silicon an n-type semiconductor. Other materials having five valance electrons are arsenic and antimony.

When trivalent impurity atoms like boron are added to a silicon crystalline structure, three valance electrons of boron atom will pair with valance electron of three neighbour silicon atoms to create three complete covalent bonds. For this configuration, there will be a silicon atom for each boron atom, fourth valence electron of which will not find any neighbour valance electrons to complete its fourth covalent bond. Hence this fourth valence electron of these silicon atoms remains unpaired and behaves as incomplete bond. So there will be lack of one electron in the incomplete bond called hole, and makes it positively charged. This makes silicon a p-type semiconductor.

When light ray strikes on the silicon crystal, some portion of the light is absorbed by the crystal, and consequently, some of the valence electrons are excited and come out from the covalent bond resulting free electron-hole pairs. If light strikes on n-type semiconductor the electrons from such light-generated electron-hole pairs are unable to migrate to the p-region since they are not able to cross the potential barrier due to the repulsion of an electric field across depletion layer. At the same time, the light-generated holes cross the depletion region due to the attraction of electric field of depletion layer where they recombine with electrons, and then the lack of electrons here is compensated by valence electrons of p-region, and this makes as many numbers of holes in the p-region. As such light generated holes are shifted to the p-region where they are trapped because once they come to the p-region cannot be able to come back to n-type region due to the repulsion of potential barrier.

As the negative charge (light generated electrons) is trapped in one side and positive charge (light generated holes) is trapped in opposite side of a cell, there will be a potential difference between these two sides of the cell. This potential difference is typically 0.5 V. This is how a **photovoltaic cells** or **solar cells** produce potential difference.



Types of Photovoltaic Cell

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:

- Mono-crystalline Silicon – also known as single-crystal silicon
- Poly-crystalline Silicon – also known as multi-crystal silicon
- Thin Film Silicon

- **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 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.

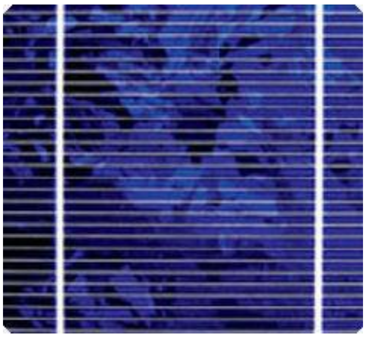
A single-crystal silicon seed is dipped into this molten silicon and is slowly pulled out from the liquid producing a single-crystal ingot. The ingot is then cut into very thin wafers or slices which are then polished, doped, coated, interconnected and assembled into modules and arrays. These types of 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.

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.

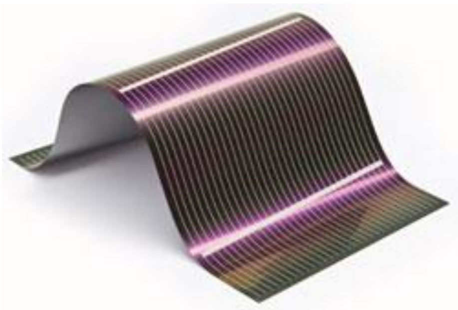
The result of this means that a poly-crystalline PV cell only has an energy conversion efficiency of between 10 to 14%. However, these types of photovoltaic cell are much less expensive to produce than the equivalent single mono-crystalline silicon due to their lower manufacturing costs.



Poly-crystalline Silicon Cell

- **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.



Thin Film Solar Cell

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 includes ***Cadmium Telluride***, ***Amorphous Silicon*** **and** ***Copper Indium diSelenide*** **or** ***CIS*.**

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*, ($CuInSe_2$). 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**

As well as 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 cell efficiency

Solar cell efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell.
Several factors affect a cell's conversion efficiency value, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values.
The efficiency of a solar cell is determined as the fraction of incident power which is converted to electricity and is defined as:

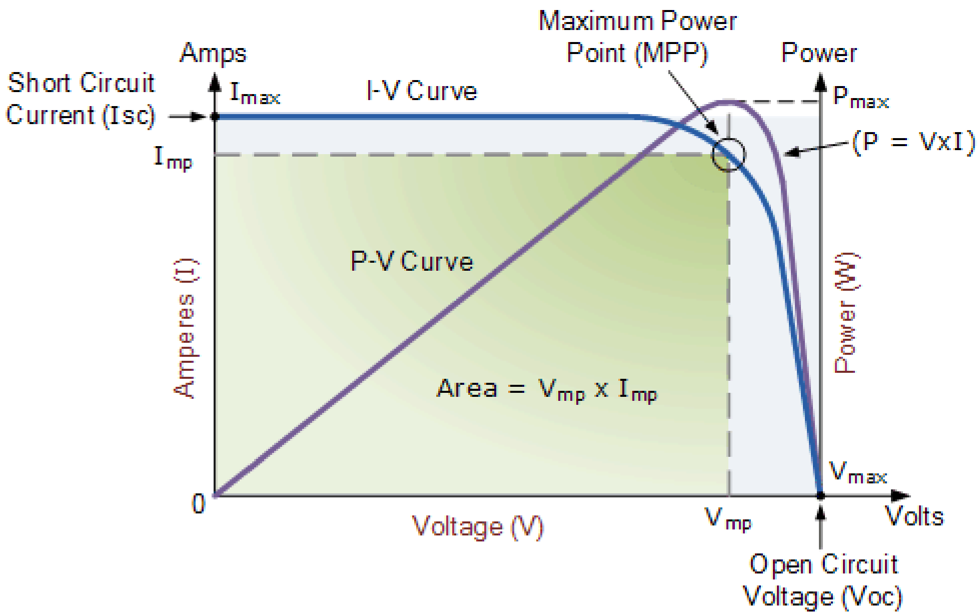
$$P_{max} = V_{OC} I_{SC} FF$$

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

where

- **V_{oc}** is the open-circuit voltage which is measured by measuring voltage across the terminals of the cell when no load is connected to the cell.
- **I_{sc}** is the short-circuit current i.e. the maximum current that a solar cell can deliver without harming its own construction.
- **FF** is the fill factor which is the ratio between maximum power point to the product of short circuit current and open circuit voltage of the solar cell.
- **η** is the efficiency
- **P_{in}** is incidence solar power
- **P_{max}** is the maximum Power Point of Solar Cell i.e. the maximum electrical power one solar cell can deliver at its standard test condition.

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 x 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 Voc. 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 Isc.
Then the span of the solar cell I-V characteristics curve ranges from the short circuit current (Isc) at zero output volts, to zero current at the full open circuit voltage (Voc). 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 Vmp. 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: Vmp ≅ (0.8–0.90)Voc and Imp ≅ (0.85–0.95)Isc. Since solar cell output voltage and current both depend on temperature, the actual output power will vary with changes in ambient temperature.

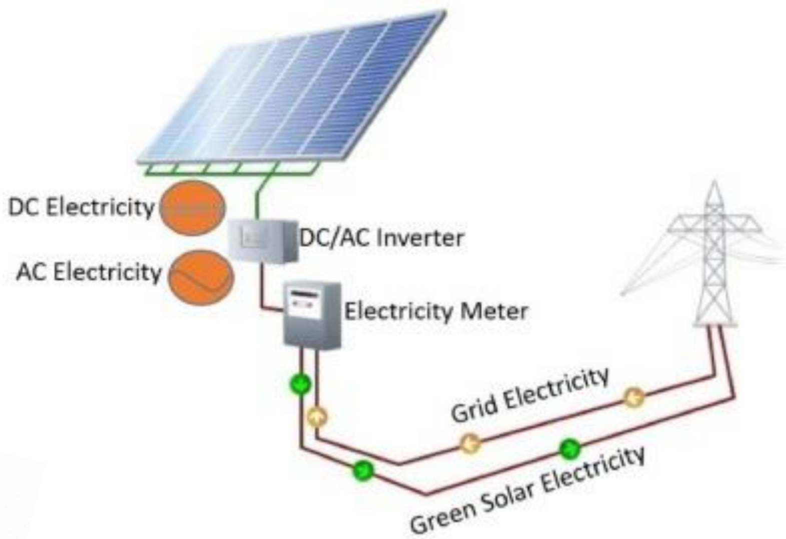
Photovoltaic System Of Power Generation

Solar photovoltaic system or Solar power system is one of renewable energy system which uses PV modules to convert sunlight into electricity. The electricity generated can be either stored or used directly, fed back into grid line or combined with one or more other electricity generators or more renewable energy source. Solar PV system is very reliable and clean source of electricity that can suit a wide range of applications such as residence, industry, agriculture, livestock, etc.

Major system components

Solar PV system includes different components that should be selected according to your system type, site location and applications. The major components for solar PV system are solar charge controller, inverter, battery bank, auxiliary energy sources and loads (appliances).

- PV module - converts sunlight into DC electricity.
- Solar charge controller - regulates the voltage and current coming from the PV panels going to battery and prevents battery overcharging and prolongs the battery life.
- Inverter - converts DC output of PV panels or wind turbine into a clean AC current for AC appliances or fed back into grid line.
- Battery - stores energy for supplying to electrical appliances when there is a demand. Load is electrical appliances that connected to solar PV system such as lights, radio, TV, computer, refrigerator, etc.
- Auxiliary energy sources - is diesel generator or other renewable energy sources.



Advantages and Disadvantages of Solar Power

Advantages:

1. Solar power is pollution free and causes no greenhouse gases to be emitted after installation
2. Reduced dependence on foreign oil and fossil fuels
3. Renewable clean power that is available every day of the year, even cloudy days produce some power
4. Return on investment unlike paying for utility bills
5. Virtually no maintenance as solar panels last over 30 years
6. Creates jobs by employing solar panel manufacturers, solar installers, etc. and in turn helps the economy
7. Excess power can be sold back to the power company if grid intertied
8. Ability to live grid free if all power generated provides enough for the home / building
9. Can be installed virtually anywhere; in a field to on a building
10. Use batteries to store extra power for use at night
11. Solar can be used to heat water, power homes and building, even power cars
12. Safer than traditional electric current
13. Efficiency is always improving so the same size solar that is available today will become more efficient tomorrow
14. Aesthetics are improving making the solar more versatile compared to older models; i.e. printing, flexible, solar shingles, etc.
15. Federal grants, tax incentives, and rebate programs are available to help with initial costs
16. No trenching is needed since the solar can be close to or at the place of installation

Disadvantages:

1. High initial costs for material and installation and long ROI (however, with the reduction in cost of solar over the last 10 years, solar is becoming more cost feasible every day)
2. Needs lots of space as efficiency is not 100% yet
3. No solar power at night so there is a need for a large battery bank
4. Some people think they are ugly (I am definitely not one of those!)
5. Devices that run on DC power directly are more expensive
6. Depending on geographical location the size of the solar panels vary for the same power generation
7. Cloudy days do not produce as much energy
8. Solar panels are not being massed produced due to lack of material and technology to lower the cost enough to be more affordable (this is starting to change)
9. Solar powered cars do not have the same speeds and power as typical gas powered cars (this too is starting to change)
10. Lower solar production in the winter months

Limitations using Solar Energy systems

The first major limitation of silicon photovoltaic (PV) cells is that they are made from a material that is rarely found in nature in the pure, elemental form needed. While there is no shortage of silicon in the form of silicon dioxide (beach sand), it takes tremendous amounts of energy to get rid of the oxygen attached to it. Typically, manufacturers melt silicon dioxide at 1500–2000 degrees Celsius in an electrode arc furnace. The energy needed to run such furnaces sets a fundamental lower limit on the production cost of silicon PV cells and also adds to the emissions of greenhouse gases from their manufacture.

second big limitation of silicon solar cells, which is their rigidity and weight. Silicon PV cells work best when they are flat and housed in large, heavy panels. But those panels make large-scale installations very expensive, which is in part why we typically see them on rooftops and big solar "farms."

The third major limitation of conventional solar cells is their power conversion efficiency, which has been stuck at 25 percent for 15 years.