SARDAR PATEL UNIVERSITY
Vallabh Vidyanagar-388120
B.Sc. (Semester - 5) Subject: Physics Course: US05DPHY26
Renewable Energy Sources
(Two Credit Course –2 Hours per week)
(Effective from June-2020)

UNIT- I Solar Thermal Energy Conversion Systems

Introduction-Subsystems, Solar Thermal Collectors, Characteristics features of a collectors, Important aspects of solar thermal Collectors, Collector Efficiency, Simple Flat plate Collectors, Installation of Flat Plate Collectors, Guidelines for Installation, Shadow Effect, Cosine loss factor and reflective Loss Factor, Heliostats with Central Receiver, Heat Transfer-fluid. **Solar Photovoltaic Systems**: Introduction to Photovoltaic systems, Merits and Limitations of Solar PV Systems, V-I characteristics of Solar Cell and Efficiency of a solar cell, Configuration of a solar PV Panel, Small and Large PV systems.

UNIT- II Geothermal Energy and Wind Energy-Fundamentals and Applications

Geothermal Energy: Introduction, Application, Geothermal Energy Resources, Origin of Geothermal Resources, Hydro Geothermal Resources. Wind Energy- Fundamentals and applications: Introduction of Wind Energy, Wind power density, Power in a wind stream, Wind turbine Efficiency, Power of a wind Turbine for given incoming Wind Velocity, Types of wind turbine –Generator Units, Mono-Blade Horizontal axis Wind turbine (HAWT), Twin- Blade Horizontal axis Wind turbine (HAWT) and Three-Blade Horizontal axis Wind turbine (HAWT).

UNIT- III Tidal Energy Conversion and Ocean Energy Technology

Tidal Energy Conversion: Introduction-Tidal range, high and low Tides, Tidal Energy Conversion, Tidal Power Ocean Energy Technology: Introduction to Energy from Ocean, Ocean Energy Resources, Ocean Thermal Energy, Ocean Waves, Ocean Tides, Advantages and Limitations of Ocean Energy Conversation Technologies, Ocean Energy Routes.

UNIT- IV Fuel Cells and Fuel Cell Power Plants

Introduction, Advantages of Fuel Cell Power Sources, Theory of Electro-Chemistry applied to fuel Cells, Principle and Operation of fuel Cells,H_2-O_2 Acidic fuel Cell, Alkaline H_2-O_2 fuel Cell, Classification and Types of Fuel Cells, Fuels for Fuel Cells, Performance Characteristics of Fuel Cells-Voltage V_c.-Current Density I_d Characteristic (Polarization Curve), Power per cell P_c, Cell Efficiency.

Books Recommended:

1. Instrumentation Measurement and Analysis
   B C Nakra and K K Chaudhary
   Tata McGraw Hill Publishing Co. Ltd., New Delhi
2. Biomedical Instrumentation
   R S Khandpur (2^{nd} Edition)
   Tata McGraw Hill Publishing Co. Ltd., New Delhi
3. Energy Technology Nonconventional, Renewable and Conventional
   S Rao and Dr. B B Parulekar
   Khanna Publishers

UNIT- I: SOLAR THERMAL ENERGY CONVERSION SYSTEMS

Introduction: Subsystems, Solar Thermal Collectors, Characteristics features of a collectors, Important aspects of solar thermal Collectors, Collector Efficiency, Simple Flat plate Collectors, Installation of Flat Plate Collectors, Guidelines for Installation, Shadow Effect, Cosine loss factor and reflective Loss Factor, Heliostats with Central Receiver, Heat Transfer-fluid. Solar Photovoltaic Systems: Introduction to Photovoltaic systems, Merits and Limitations of Solar PV Systems, V-I characteristics of Solar Cell and Efficiency of a solar cell, Configuration of a solar PV Panel, Small and Large PV systems.

Introduction to Solar thermal energy: Approximately 30 percent of the solar energy impinging on the earth is reflected back into space. The remaining 70 percent, approximately 120,000 terawatts [l terawatt is equal to 10^{12} watts], is absorbed by the earth and its atmosphere. Solar radiation reaching the earth consists of the beam radiation that casts a shadow and can be concentrated and the diffuse radiation that has been scattered along its path in space from sun to earth. The solar radiation reaching the earth degrades in several ways. Some of the radiation is directly absorbed as heat by the atmosphere, the ocean, and the ground.

This topic is regarding to the various solar-thermal energy systems and solar thermal power plants.

The solar thermal energy conversion systems are classified into the following categories of applications in the order of rising cost and complexity:

Categories:

1. Low temperature applications (<150℃) with non focusing collectors.

2. Medium temperature applications (150℃ to 300℃) with line focusing collectors tracking in one plane.

3. High temperature applications (500℃ to 1000℃) with point focusing collectors and tracking in two planes.

- Solar thermal collector system gathers the heat from the solar radiation and gives it to the heat transport fluid.
- The solar heat fluid receives the heat from the collector and delivers it to the thermal storage tank, boiler steam generator, heat exchange etc. Heat transport fluid is called primary coolant.
- Thermal storage system stores the heat for a few hours. The heat is released during cloudy hours and at night.
- Thermal-Electric Conversion System receives thermal energy and drives steam turbine generator or gas turbine generator. The electrical energy is supplied to the electrical load or to the AC grid.
- In Co-generation plants heat in the form of hot water or steam may also be supplied to the consumer in addition to the electrical energy. In this case, hot water/steam from the reservoir may be pumped through outlet pipes to the load side.
- Applications of solar thermal energy systems range from simple solar cooker of 1 kW rating to complex solar central receiver thermal power plant of 200 MW rating.

Presently the solar thermal electric power plants are considered to be economically viable only in locations having favourable sunlight throughout the year and the fossil fuels/hydro resources etc. are not available in the vicinity.

Subsystems:

The complete solar thermal energy conversion plant has several subsystems. Each subsystem has certain functions; required subsystems are assembled to form the plant.

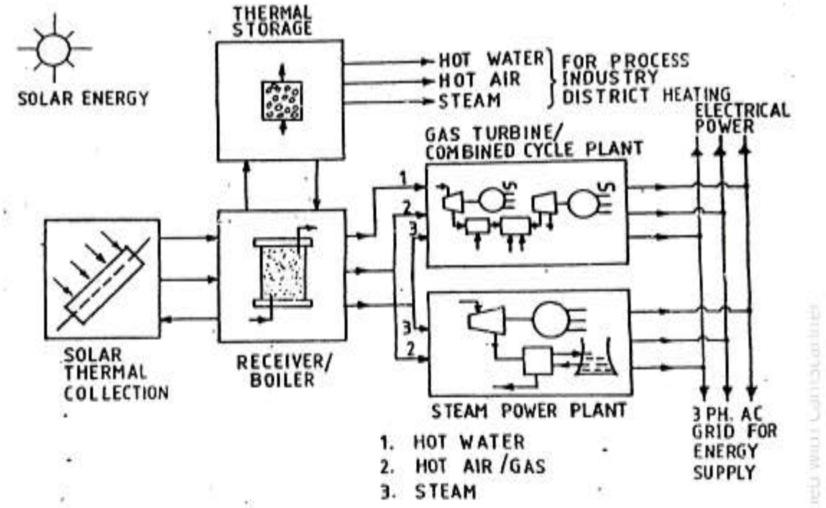


Fig. 4.1. Subsystems in Solar Thermal Energy Conversion Plants. Some subsystems shown in the schematic are optional.

The essential subsystems are:

- Solar thermal collectors or reflectors (concentrators)
- Heat transport fluid system
- Thermal storage system
- Thermal receiver
- Heat exchanger
- Distribution system for hot water, steam
- Solar-thermal-electrical power plant
- Electrical substation and distribution system
- Auxiliaries.

Table 4.1
Subsystems in Solar Thermal Energy Conversion Plants

Subsystem Refer Fig. 4.1‡	*Hot Water Plant*	*Steam Plant*	*Solar Central Receiver Power Plant*	*Solar Distributed Collector Power Plant*
Collector				
Flat plate	✓			
Paraboloid-through	✓	✓		✓
Heliostat-reflector		✓	✓	
Fresnel		✓		
Heat transport fluid	✓	✓	✓	✓
Thermal storage tank	✓	✓	✓	✓
Boiler / steam generator		✓		✓
Steam-turbine, generator or gas turbine, generator, electrical substation			✓	✓
Central receiver on tower			✓	
*Heat exchanger with water to working fluid**				✓

‡ Some subsystems listed in this table are optional.
* For Binary cycle plant.

It is a combination of the Solar Collection System and Thermal Electrical Power Plant. The thermal plant is either steam-turbine type or Gas Turbine Type or Combined Cycle Type.

Schematic Diagram:

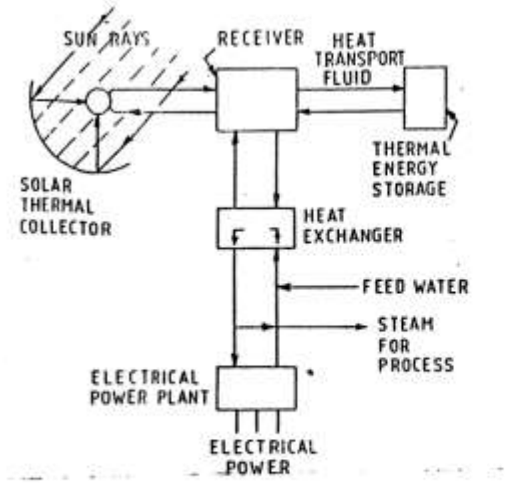


Fig. 4.2. Schematic of a Solar-Thermal Electrical Power Plant.

Fig- 4.2 illustrates the scheme. The thermal collector receives solar energy and the heat-transport fluid (water) is heated. 'The heat-transport fluid is circulated through the receiver.

The thermal storage tank stores heat in the form of hot water and solids. Heat exchanger delivers hot water; steam to process plant or to electrical power plant.

The schematic is finalized on the basis of design requirements of the plant.

SOLAR THERMAL, COLLECTORS, CONCENTRATORS, REPLECTOES

<u>Solar Thermal Collectors:</u>

Solar power has low density (kW/m), Hence a large area on the ground is covered by the collectors. The collectors receive the heat from solar rays and give it to the heat-transport fluid. Flat-plate collectors are used for low temperature applications. For achieving higher temperature of heat transport fluid, the sun rays must be concentrated or focussed. The following types of solar thermal collection systems are in practical use for medium and high temperature applications.

1. Dispersed or Distributed receiver systems of, either

-Parabolic through collectors with line focus, or

-Paraboloidal Dish collectors with point focus.

Each collector individually heats-up its own receiver.

Receivers are connected with piping system for the flow of fluid

2. Central Receiver Systems (CRS):

Several heliostats on ground level reflect the sun light to the single central receiver on a tall tower.

The purpose of solar Thermal Collectors, concentrators and reflectors is to draw as much power from the sun light as possible.

- The solar thermal collectors gather the thermal energy from solar radiation and deliver it to the thermal transport fluid (either liquid or gas).

  The solar thermal collector types include:

-Flat plate collectors.
-Modified flat-plate collectors.
-Paraboloidal dishes.
-Fresnel lens type.
-Parabolic through.
-Central receiver with heliostat reflectors.

Characteristic features of a collector:

The sun light is gathered by the thermal collector by various methods.

The important features of a collector system are:

Whether focusing or non-focusing?

Temperature of working fluid attained:

-Low temperature, Medium temperature, High temperature.
-Non-tracking type or tracking in one plane or tracking in two planes?
-Distributed receiver collectors or central receiver collectors?
-Simple and low cost or complex and costly?
-Layout and configuration of collectors in the solar field.

Table 4.2. Characteristics and Features of Solar Thermal Collector Systems

Type of Collector	*Temperature of working fluid*	*Principle of Collection*	*Sun-tracking requirement simplicity and cost*
1.1. Simple Flat Plate 1.2. Modified Flat Plate	— Low temperatures around 150°C — C.R = 1 — Temp. = 200°C — C.R. = 1.2	Radiation received by the surface without focussing. Surface gets heated. — Both beam and diffuse component are collected. — Distributed collectors.	— Usually not provided as too costly. — Fixed location with certain tilt angle — Simple, low cost
2. Parabolic through Type Collector with line focus	— Moderate temperatures around 300°C. — C.R. = 2 to 100	Parabolic through shaped mirrors reflect the beam radiation on axial pipe. — Line focus on central axis. — Pipe on axis absorbs energy and transfers to working fluid — Only beam radiation collected — Distributed collector.	— Tracking in one plane for daily movement of the sun. — Adjustment of orientation for seasonal variation — Moderate cost.
3.1. Paraboloidal dish with point focus distributed collector or 3.2. Fresnel lense point focus distributed collector	— High temperature around 1000°C or higher C.R. = 200 to 10000	— Paraboloid dish shaped reflectors focus the reflected high rays on the centre of paraboloid — Point focus — Reservoir containing heat transport fluid located at focal point — Distributed collector system — Only beam radiation is collected.	— Requires tracking in two planes for daily and seasonal orientation. — High cost.
4. Central receiver and central focus with heliostats on ground level	— High temperature 1200°C C.R. = 200 to 1000	— Several nearly flat mirrors on ground reflect the beam radiation on a central receiver/furnace on a tall tower. — Heat transfer fluid in central receiver absorbs energy. — Only beam component of sun-light is reflected. Diffuse component is not reflected.	— Mirrors must track the sun individually in two planes — Most complex, higher cost.

Important aspects of Solar Thermal Collectors:

Sun light has low power density (0.1kW/m^2 to 1kW/m^2). Hence, very large surface area of the collectors is required for producing rated power of1 MW. Efficiency of thermal collectors is very important.

This depends on collector layout, collector tracking, atmospheric clarity, etc.

Concentration ratio:

Other important features of a solar collector system is concentration ratio and temperature range.

$$\textbf{Concentration Ratio (CR)} = \frac{\frac{kW}{m^3}\ \textbf{IN SOLAR RADIATION ON SURFACE}}{\frac{kW}{m^3}\ \textbf{ON SURFACE OF FOCUS ONF COLLECTOR}}$$

Flat-plate collectors have concentration ratio of only 1. The resulting temperature of heat transfer fluid is less than 150°C. Focusing of collectors attain higher temperatures. Concentration ratios of the order of 1000 can be obtained with heliostats with sun-tracking in two planes. Concentration ratios up to 100 can be achieved by parabolic through collectors with sun tracking in one plane.

Collector Efficiency:

The performance of a collector is evaluated in terms of its collector efficiency. The collector Efficiency is the ratio,

$$\textbf{Collector Efficiency} = \frac{\textbf{Energy collected by the collector in Joule}}{\textbf{Energy incident on the collector in Joule}}$$

For given ratio of solar isolation (W/m^2), the collector efficiency decrease with the increasing difference between the collector temperature and outside temperature.

With larger collector surface, higher collector temperature and higher temperature difference is obtained resulting in lower efficiency. If higher temperature is desired, relatively larger collector surface would be necessary to gather the same amount of energy than that at a lower collector temperature. Solar collector cost is a significant component of installation cost. Hence it is important to keep unit cost of Collectors low and total surface area of collectors as small as possible. Flat plate collectors are used for low temperature applications only. They are not economical for high temperature application. They are not suitable for high temperature applications and solar electric power plants.

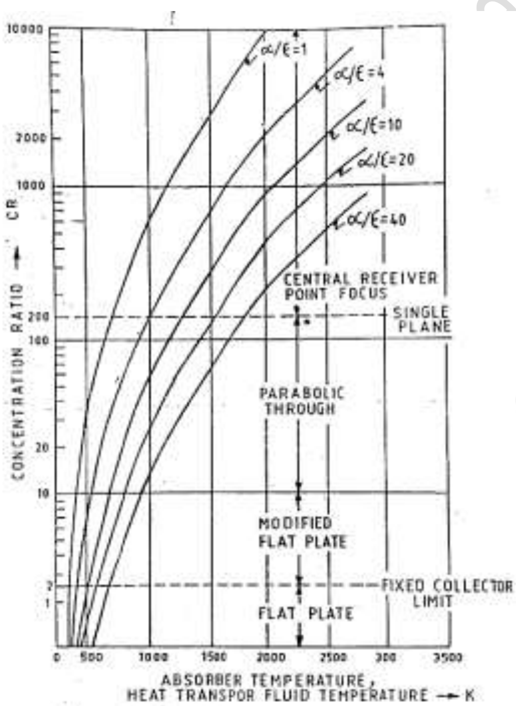


Fig. 4.3. Characteristics of various types of collectors. α/ε = Absorbtion/Reflection ratio of collector surface.

Absorption/Reflection ratio (α/ε) of the collectors surface has a significant effect on the temperature attained by the heat transport fluid. Absorption/Reflection ratios are in the range of 1 to 40. Figure 4.3 gives graphs of concentration ratios for various types of collectors and for various values of Absorption/Reflection ratio.

The Simple Flat Plate Collectors:

The simple flat plate collector has a coated flat heat absorber plate with channels or tubing in contact with the plate for passage of working fluid. Transparent covers of glass sheet are placed on the upper side of the absorber plate to reduce thermal losses. Thermal insulation is provided between the absorber plate and the casing. The total panel is installed on a support structure.

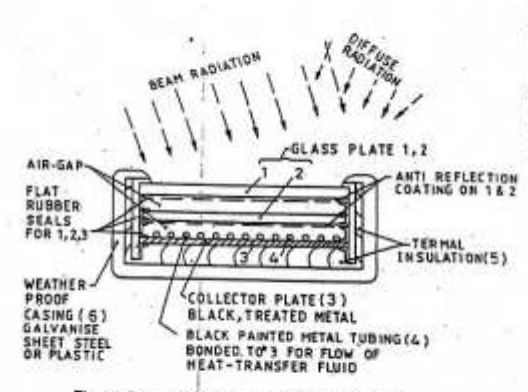


Fig. 4.4. Cross section of a flat plate thermal collector.

Flat plate collectors absorb both beam and diffuse components of radiant energy. Hence they can function without need for tracking the sun. Also they absorb energy even during cloudy and hazy atmosphere. Simple flat plate collectors are most widely used for solar thermal energy systems. Concentration ratio is 1. Hence temperatures achieved are low (around 100 ℃), applications include:

-Solar water heating systems for residence, hotels, industry.

-Desalination plant for obtaining drinking water from sea water.

-Solar cookers for domestic cooking.

-Drying applications.

-Residence heating.

The simple method of collecting solar energy is by means of Flat-plate collectors. The heat transfer fluid is either liquid or gas. Simple flat plate collector is shown in Fig. 4.4. The absorber plate is a specially treated blackened metal surface. Sun rays striking the absorber plate are absorbed the absorber plate resulting in the temperature rise of the absorber plate. Heat transport fluid is circulated through the tubing which is in intimate contact with the absorber plate. The heat is transferred from the absorber plate to the heat transport fluid.

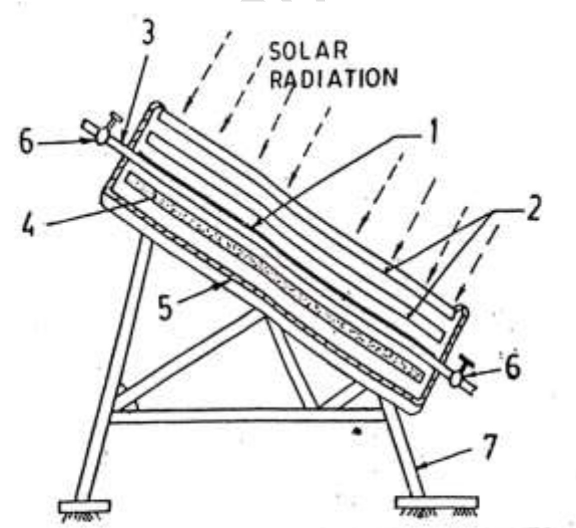
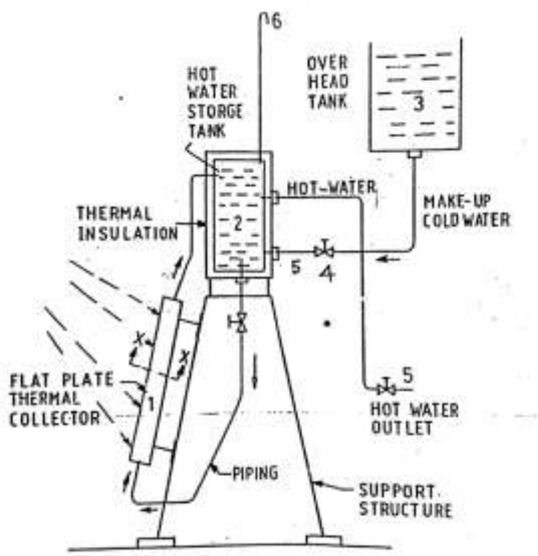


Fig. 4.5. Flat plate collector for low temperature water heating.

1. Absorber plate (Treated, blackened, metallic plate)
2. Transparent covers (Glass or plastic)
3. Fluid Passage collector tube fitted below 2.
4. Thermal insulation.
5. Metal casing.
6. Connection to next panel.
7. Fabricated galvanized steel support.

Another difficulty arises with the surface emission. Generally a good absorber surface is also a good emitter surface. Collector efficiency can be improved by selective surface which has high absorptance for sun light and low emittance of radiation. Selective surfaces for absorber plates are usually manufactured by plating and depositing process on metals. The outer glass is provided with anti-reflection coating from inside. The second glass cover is provided with infrared reflector coating. At given collector temperature, collector efficiency may be improved by (1) Selecting absorber surface and (2) Anti reflection coating for the glass covers. **Installation of Flat Plate Collectors:** Fig. 4.6 shows installation of a flat-plate water heater with natural circulation of water by convective flow, Hot water flows to the higher level and remains in the storage lank. The displaced cold water from the bottom of the storage tank allows to the collector.

Hot water for consumption is tapped from the upper level of the hot water storage tank. Make-up cold water is taken from an over head tank. Fig-12.6(c) shows a schematic of a larger system.



1. Collector
2. Storage tank
3. Make-up cold water tank
4. Cold water inlet
5. Hot water outlet
6. Air vent

Figure: 4.6. Installation of a flat-plate collector for water heating system

Positioning of the Flat-Plate collector: Due to low collection efficiency of flat-plate collector it is uneconomical to arrange sun tracking.

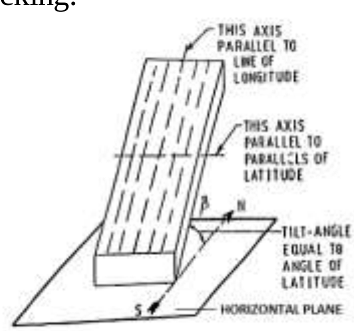
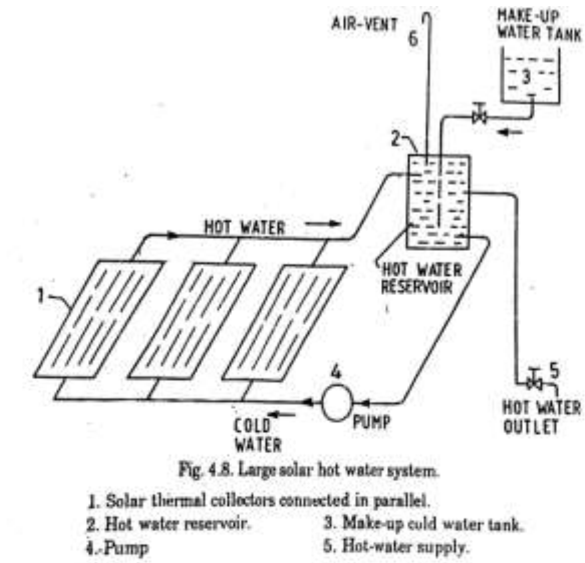


Figure: 4.7. Positioning of the Flat-Plate collector

Hence fixed type installation is preferred. The axis of the pipes is placed parallel to the parallel lines of longitude passing through the north and south poles. The plane of the collector plate is placed at tilt angle (β) equal to the angle of latitude (ϕ) for the location. Refer fig. 4.7.

Guidelines for Installation:



1. Solar thermal collectors connected in parallel.
2. Hot water reservoir.
3. Make-up cold water tank.
5. Hot-water supply

4-Pump

Fig-4.8 Large solar hot water system

-Tilt angle (ß) should be equal to the angle of latitude of the location.
- In the northern hemisphere, the collector surface should face the south.
-The longitudinal axis of the collector shall be parallel to the lines of longitude.
-The horizontal axis of the collector shall be parallel to the lines of latitude.
-Pipes of heat-transport fluid (water) shall be parallel to the longitudinal inclined plane. This will help in natural convection of the heat transport fluid.

For larger installation, several collector panels are connected in parallel as shown in Fig. 4.8. Solar window through shadows, extreme position of sun and angle of latitude must be clearly identified.
The efficiency of the collector system is adversely affected by the shadow, cosine loss, dust etc. These aspects have a decisive influence on the design of the collector layout.

1. Shadow Effect: Shadows of some of the neighboring collector panel fall on the surface of the collector particularly when the angle of elevation of the sun is less than 15° (around sun-rise and sunset). The shadow effect is reduced as the angle of elevation of the sun increases.

$$\text{Shadow factor} = \frac{\text{Surface of the collector receiving light}}{\text{Total surface of the collector}}$$

Shadow factor is less than 0.1 for angle of elevation of sun lesser than 15 degrees. Shadow factor is 1 during noon when angle of elevation of sun is nearly 90° and shadow of the collectors does not fall on the neighboring collector. The effective hours of solar collectors are between 9 AM and 5 PM around 21st March, in the northern hemisphere, for angle of elevation of sun more than 15°.

2. Cosine Loss factor: For maximum power collection, the surface of collector should receive the sun rays perpendicularly. If the angle between the perpendicular to the collector surface and the direction of sun ray is 6, the area of solar beam intercepted by the collector surface is proportional to cos6. Hence solar power collected is proportional to Cosθ. For fixed type collector panel's cosine loss varies due to the daily variation and seasonal variation of the direction of sun rays.

3. Reflective Loss Factor: The collector glass surface and the reflector surface collect dust, dirt, moisture. The reflector surface gets rusted, deformed and looses the shine. Hence the efficiency of the collector is reduced significantly with passage of time. Preventive measures are:

-Daily maintenance (Cleaning).
-Seasonal maintenance (Cleaning, touch up paint)
-Yearly overhaul (Charge of seals, cleaning after dismantling).

Heliostats with Central receiver: Heliostats are nearly flat faced reflecting mirrors with provision of tracking the sun in two planes. Several thousand heliostats are mounted on independently tracking-structures on ground level. Each heliostat should have individual tracking control.

Reflected rays are focused on to the central receiver mounted on a tall tower. High temperatures are achieved. Heliostat central receiver systems are used for solar thermal power plants. The controls are complex and costly. Collectors cover a very vast ground area.

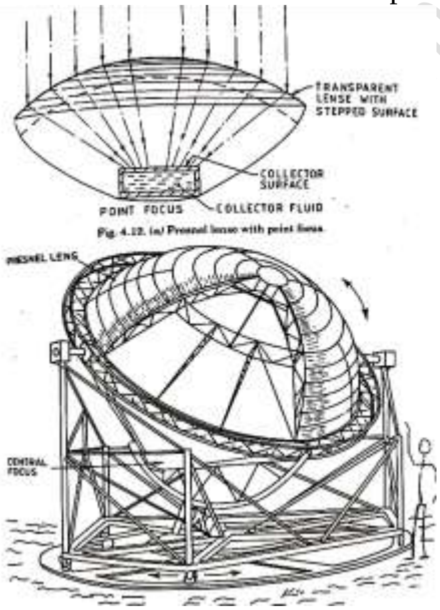


Fig- 4.12 (a) Fresnel lens with point focus
Fig- 4.12 (b) an overview of a large Fresnel Lens with point focus

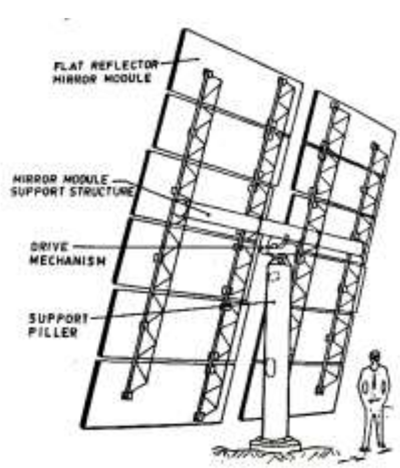


Fig- 4.13 Flat mirror heliostat (rear view)
Size: 36 m; 12 pieces of mirror each 1x3 m.

Heat Transfer fluid (Primary Coolant):

The heat transfer fluid (Primary Coolant) is pumped through the collector piping. The thermal energy collected by the solar collectors is given to the heat transfer fluid. The heat transfer fluid flows from the collectors to the central receiver or storage tanks.

The heat transfer fluid may be same as the working fluid of the thermodynamic cycle or it may be different.

The following five heat transfer fluids have been envisaged for practical solar thermal systems.

1. Water-steam (being used).
2. Liquid metals for e.g. Sodium (Na).
3. Molten salts for e.g. Nitrate salt mixtures.
4. Gases such as air, nitrogen, helium.
5. Heat transfer oils.

Table 4.2 Characteristics of Heat Transfer Fluids

Name of the system	*Remarks*
1. Water-Steam	— Low development cost, well established technology. — Used as heat transfer fluid and working fluid. — Steam temperature 540 to 600°C. — Steam pressures 70 to 140 bar. — Used for distributed receiver system and central receiver system. — Less efficient heat transfer fluid.
2. Liquid metals	— Sodium (Na) system under development — High heat transfer coefficient. — More compact receiver — Sodium freezes at 98°C requires auxiliary heating during shut down. — Cover gas such as argon used to prevent oxidation. — Operating temperature 540°C. — Boiling point 883°C. — Do not required high pressurisation.
3. Molten salts	— Nitrate salt mixtures under consideration. — High operating temperature. — Freezing point 140 to 220°C. require auxiliary heating.
4. Gases	— High temperatures (Above 840°C) — Pressurisation necessary to increase mass-flow rate. — Air, Nitrogen and helium are considered. — Used as heat transfer fluid or working fluids.
5. Heat transfer oil	— Low corrosion or pipes and receiver — Decomposed at higher temperature. — Temperature range — 7 to 300°C. — Used as heat transfer fluid. — High mass flow rate and heat transfer coefficient.

SOLAR PV SYSTEMS:

Introduction to Photo-Voltaic Systems:

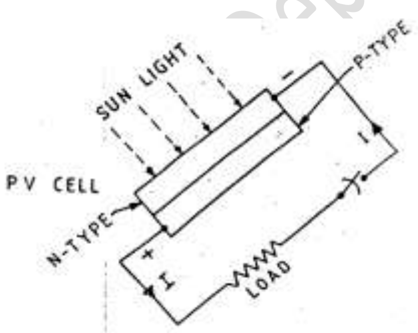


Fig- 5.1 Schematic of a PV-Cell (Solar Cell)

Solar PV systems have become commercially successful during 1980s. Solar PV technology is the most significant renewable energy technology particularly for remote and stand-alone consumers away from main electrical distribution network.

The Solar Photo-Voltaic cells (PV cells) convert the incident solar light energy directly to electrical energy in DC form.

A single cell has a rated voltage of about 0.5 V and rated power of about 0.3 W.

The principles of solar energy, solar spectrum, flat plate collectors, parabolic through collectors with line focus etc. are applicable to PV collectors.

Several cells are connected in series/parallel to obtain desired voltage and power.

In solar PV systems the intermediate thermal energy stage is omitted and the energy is converted directly from the solar energy form to electrical energy form. Therefore problems of high temperature materials and excessive thermal loss are absent.

The vital component in a Solar PV system is the Solar Cell, also called Photo-Voltaic Cell (PV Cell). A solar cell is a small semiconductor device which has a light-sensitive N-P junction. When solar light rays strike the N-P junction, DC e. m. f. is generated with P terminal as positive and N-terminal as negative.

Nominal ratings of a typical single PV-cell when exposed to full sun light gets:

- Current 0.75 A, DC
- Voltage 0.45 V, DC
- Power 0.33 W

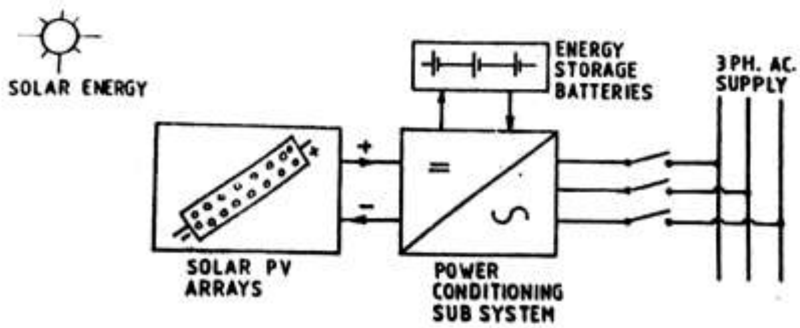


Fig. 5.2. Schematic of a solar PV system.

Actual power delivered varies with intensity of sun light and the load resistance. When exposed to sun light, the solar cell acts like a tiny DC cell. Several Solar cells are connected in series, parallel to get desired voltage, current and power.

Several Solar cells are connected in series to form a string. Several strings are connected in parallel to form a module. Several modules are connected in series, parallel, series-parallel configuration to form an Array. The arrays installed on the structure to form a solar PV collector.

A Solar PV panel (Solar PV Array) delivers certain DC current at certain DC voltage for certain intensity of incident solar energy. The DC output power depends upon total number of cells and power per cell. The current and voltage are influenced by the circuit connections and external resistance.

Solar PV-panels are installed outdoors in a position to receive maximum sun light during the day, and a year. Solar PV panels may be fixed type or tracking type; without focusing or with line focusing or with point focusing etc. Fixed type Flat plate fixed panels without focusing are commonly used as they are simple, cheap and maintenance free.

The Solar PV panels deliver DC electrical power only during favourable conditions of sun light. To obtain electrical power during cloudy weather or during nights the energy storage batteries are necessary. During the favourable sun light hours and low load the storage batteries get charged. During nights and cloudy weather, the storage batteries supply the electrical energy to the load. It is generally uneconomical to install storage batteries for supplying the energy requirement of the load beyond a few hours. Some of the electrical require 50 Hz AC supply. Hence DC power supplied by the solar PV panel and the storage battery should be converted to

single phase or three phase, 50 Hz, AC power. DC to AC inversion is achieved by means of static inverters. These are incorporated in the loads power conditioning unit.
The AC waveform is regulated
and made of desired quality by the conditioning unit the power conditioning unit is provided on the output side of a PV-paved for
- Improving AC waveform by harmonic filters
- Regulating the voltage
- Inverting DC to AC and
- Protective control, and monitoring functions.

Merits and Limitations of Solar PV Systems:

The merits of PV systems are
-Use of clean, cheap, noiseless, safe, renewable solar energy to
produce electrical energy at the location of utilization, conservation of non-renewable fuels.
-Suitable for remote loads away from main electrical network and at places where other fuels are scarce and costly.
- Cost of installation of long distribution lines, distribution substations etc are eliminated.
- Suitable for portable or mobile loads e.g. radio sets, cars, buses, Space-Crafts.
- Reliable service, long life (15 years).
- Modest maintenance

The Limitations of PV systems:

-Irregular, intermittent supply of solar energy.
-Need for storage batteries.
-High capital cost (Rs/k W) due to large number of PV cells, low output power, low efficiency and high technology involved.
-Not economical for central power plants of MW rating due to very large area of PV panels and very large storage battery system.
Require storage batteries and or additional diesel generator sets for supplying power during night and during cloudy periods,
Do not generate power during cloudy season. Not suitable
during rainy season.
Space for installing large PV-panels is not available in large
cities, industrial cities, etc. except on roofs of buildings.
Advanced PV-technology required for producing PV-cells.
-Very low efficiency of PV-cells (10 to 14%)

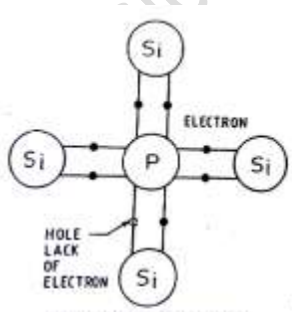


Fig. 5.3. P-type Semiconductor (Silicon crystal doped with 'P'-type impurity)

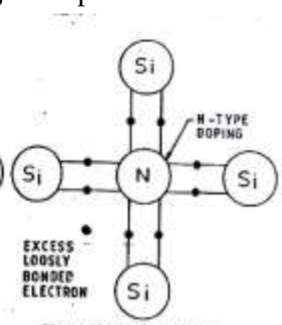


Fig. 5.4. N-type Semiconductor (Silicon crystal doped with 'N'-type impurity.

Principle of a Photo-Voltaic Cell:

The PV cell (Solar Cell) is a light sensitive, two terminals, and semiconducting N-P junction made of semiconducting material such as

silicon. A solar cell has two layers called N-type and P-type and two corresponding electrodes, negative and positive. N-type material is obtained by doping silicon crystal with N-type impurity (Fig. 5.4). P-type material is obtained by doping silicon crystal with P-type impurity.
The N type layer is thin and transparent. The P-type layer is thick. When sun light strikes the N-type thin layer, some of the waves of light energy penetrate up to P-type layer. The energy from Photons in the light waves is imparted to the molecules and atoms in the –P junction resulting in liberation of electron-hole pairs. Electrons are released from N-type material and holes are created in P-type material. Electrons are negative charges and holes are positive charges (lack of electrons).

When external electric circuit is completed by connecting electrodes to the load, the electrons flow in the closed external circuit from N-type terminal (negative) to P-type terminal (Positive). Direction of current (by conversion) is from the positive terminal (P-type) to negative terminal (N-type) in the external circuit.

Within the N-P junction 'electron-hole' pairs are continuously generated during the incidence of the sunlight. Energy from so1ar rays is captured by the solar cell and is converted directly to electrical energy. Thermal energy state is absent. Energy conversion is directly from Solar (wave) energy to electrical energy.

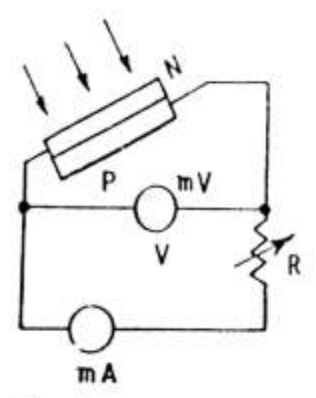


Fig. 5.5. Test condition.

Most of the commercially available solar cells are with silicon crystals treated with following compounds

Cadmium –Sulphide	Cadmium –territide
Gallium-Arsenide	Indium- Phosphate
Zinc –Sulphide	Cadmium –Selenide
Gallium-Antimonite	

V-I Characteristics of a Solar Cell:
The voltage, current and power delivered by the solar cell are influenced by:
- Conditions of sunlight, intensity, wavelength, angle of incidence etc. Visible band gives maximum power.
-Conditions of the junction, temperature, termination, etc.
-- External resistance (R)
Hence the ratings of a solar cell are specified for particular reference conditions and with the help of V-I characteristics. The V and I are direct voltage and direct current measured in the PV-cell circuit during full sunlight.
Fig. 5.5 represents a test condition and Fig. 5.6 gives V-I characteristics of a typical commercially available solar cell.
When external resistance R is very high (Mega-Ohms) the condition is called Open Circuit. The Open circuit voltage Voc of a solar cell is about 0.5 V D.C. It is the maximum voltage across a

PV cell. Open circuit current is zero. External resistance R is very high in Mega-ohm range or infinity.

If external resistance R is reduced gradually and the readings of terminal voltage V and load current I are taken, we get the V-I characteristic of the PV-cell as shown in Fig. 5.6.

As the values of external resistance is reduced from high value to low value the terminal voltage of the cell falls and current increases. A steep characteristic OX is obtained.

At knee point **K** the characteristic undergoes a smooth change and becomes flat for the portion **K-S**. When the external resistance is completely shorted, the short circuit **Isc** is obtained. The terminal voltage for the short circuit conditions is zero. Maximum current delivered by a solar cell is the **Isc**.

The current curve is almost flat between the knee point and the short circuit. Hence a solar cell is called a constant current source with current output, nearly equal to short-circuit current.

Operating point voltage (**Vc**) is dictated by the external resistance (**R**) but the current remain almost constant for the portion **S-K.** For constant current **Ic, Vc=Ic·R.**

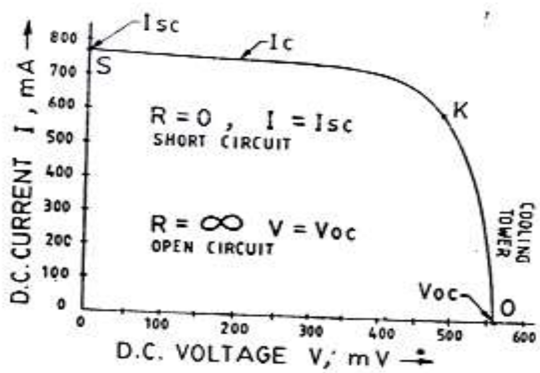


Fig. 5.6 (a)

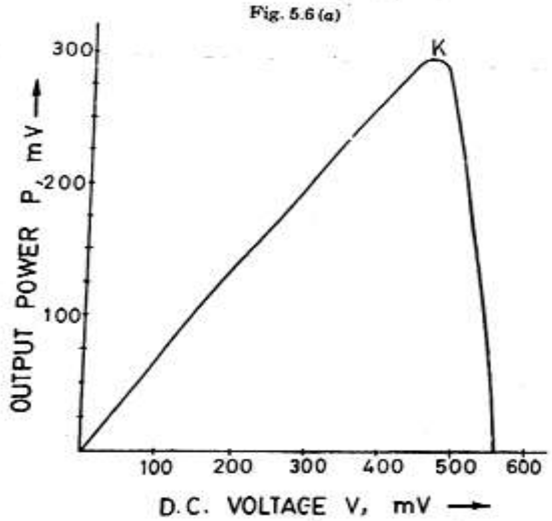


Fig. 5.6. (b) Efficiency curve of a solar PV cell. K corresponds to knee point Fig. 5.6 (a).

Three important points on the **V-I** characteristic of a solar cell are

Open Circuit Point (**O**)

Knee Point (**K**)

Short Circuit Point (**S**)

operating range is the flat current portion **KS**.

Power of a Solar Cell and Solar PV Panel:

Solar cell delivers electrical power (**Pc**) given by

Pc= Vc·Ic ....Watts

where, **Pc** = Power of one cell, watts

Vc = Voltage at terminals of the Cell, DC, Volts

Ic = Current delivered by the cell, DC, Amperes.

For full incident light, a single PV cell delivers power **Pc** which varies with the position of the operating point on the **Vc - Ic**, characteristic. The exact point of operation is detected by the external load resistance **R**.

Fig. 5.7 shows power characteristic of a typical solar cell with full incident light. Point Pc is obtained by multiplying **Vc** and **Ic**

Pc is zero at open-circuit point **O**
Pc is zero at short-circuit point **S**
Pc is maximum at knee point **K.**
Between the knee point **K** and short-circuit point **K**, the **V-I** characteristic is with flat **I** and the power goes on reducing as the point moves from the knee point K to the short circuit point **S**.
It is preferable to operate a PV cell with maximum possible light and at knee point **K** for obtaining maximum power and therefore maximum efficiency.

Power of a Solar Panel, Array and Module:

Let **n** = Number of solar cells in a module
m = Number of modules in an array or a panel
Pc= Power per solar cell, watts

Power per module = **nPc**
Power per array or panel = **m x n xPc**

Pp = m x n xPc …W

For full light, solar panel will deliver power **Pc**. With power (**Pc**) and external resistance (**R**), the voltage and current can be calculated DC voltage of the PV panel **Vp**, current delivered by the PV panel (**Ip**) and the external DC load (**R**) are correlated by the basic equations of the ohms law,

$$P_p = \frac{{V_p}^2}{R} = {I_p}^2 R = V_p I_p$$

Power of a Solar Panel = **Pp** watts

Pp = m x n Pc

Voltage across panel $V_p = \frac{P_p}{I_p}$

Current delivered by panel $I_p = \sqrt{\frac{P_p}{R}}$

Interconnections of Solar Cells:

During the manufacturing process, each solar cell is tabbed to provide connectors. Tabs are thin metal pieces which are bonded to the solar cell metallization pattern.
Solar cells are interconnected as shown in Fig. 5.7 by any of the following soldering techniques.

1. Pulse/Parallel gap
2. Soldering iron
3. Infra-red heating
4. Induction heating
5. Laser
6. Vapour phase reflow

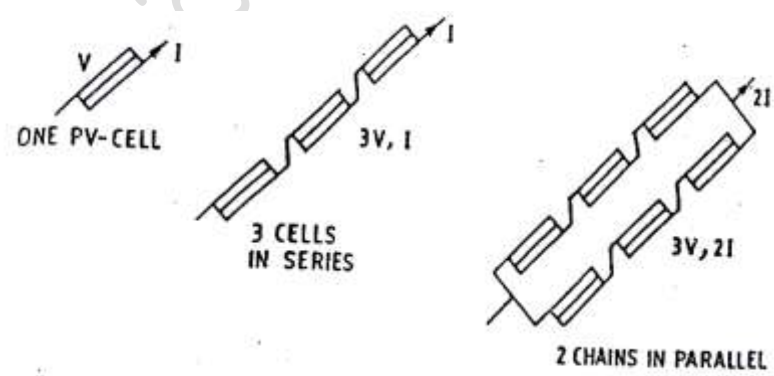


Fig. 5.7. Connections of PV-cells.

To form a module cell strings are connected in series, parallel as shown in Fig. 5.7.

Efficiency of a Solar Cell:

Most of the manufacturers give the efficiency values of the solar cells on the basis of the following definition:

$$\textbf{Efficiency of a solar cell} = \frac{\textbf{Incident radiation (W)}}{\textbf{Power delivered (W)}}$$

for specified conditions of temperature, Irradiance solar spectra.

Typical standard test conditions for efficiency measurement are:

Irradiance 1000 W/m or 800 W/m

Cell temperature 25°C to 45°C

Maximum efficiency occurs at:

Full solar radiation on the PV cell

Knee point on V-I curve [Fig. 5.6 (b)]

Maximum efficiency of a particular solar cell depends on the materials, design parameters, manufacturing process, test conditions etc. and the efficiency range of commercially available solar cells is 12 to 15 per cent.

Maximum efficiency achieved in laboratories is between 15 to 20 per cent. Maximum theoretical efficiency is 25 per cent.

The maximum efficiencies for various types of silicon used for the PV cells are reported to be between 5 to 14%.

Efficiencies of PV cells:

Cell Efficiency	1980s
With amorphous silicon	5%
With polycrystalline silicon	7%
With single crystalline silicon	12%

The values have been further improved during 1990s.

The complexity of manufacturing process and the cost of cell are maximum for single crystalline silicon cell and least for amorphous silicon cell the maximum efficiencies of commercial solar cells are likely to touch 20% by 1996.

Efficiency of Solar PV Module:

The-module efficiency is lesser than cell efficiency due to lesser area coverage factor (Solar cell area/module area). Rectangular solar cells have higher surface coverage area than round cells. Hence rectangular cell modules have higher efficiency than round cell modules.

Spectral Response:

The sun rays comprise waves of various frequency bands which include

- Infrared band
- Visible band
- Ultra-violet band

The types of wave-bands reaching the PV cells mounted in a Solar PV panel is influenced by the wave lengths in the scattered, beam and global radiation and received by the collector.

Wave lengths absorbed, reflected, scattered by the covering glass of the collector and the reflecting surface of the concentrating parabolic through or Paraboloidal dish etc.

Spectral Response of a solar cell is a curve of the power delivered by a solar cell plotted against frequency of incident light waves.

The solar cell gives maximum output with visible frequency band in light waves.

Configuration of a Solar PV Panel:

1. Solar Cell Module:

A module is a smallest non-divisible, self contained, environmentally protected unit with a transparent cover. Several solar cells and with interconnected in series, parallel, series-parallel. A module has two terminals and delivers certain DC output when exposed to full sunlight.

Pm =nPc ...Watts

Pm= Power of one module, watts

Pc= Power of one cell, W

n = Number of cells in a module.

2. Solar Array:

An array has several modules connected in series, parallel, series/parallel and delivers DC power through two terminal leads.

Power of an array **Pp**

Pp = n · mPc

n = number of cells in a module

m = number of modules, in a panel.

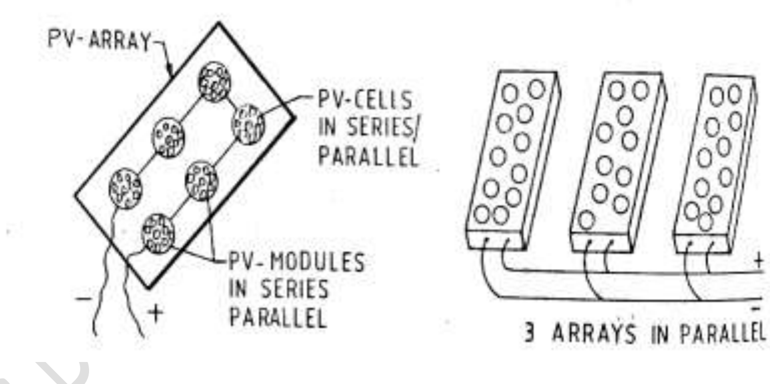


Fig - 5.8 Connections of PV-modules and arrays

Fig. 5.8 shows interconnections of solar PV modules to form an array. Configuration of the solar PV array (Solar Collector) is selected to obtain desired voltage and current by suitable series, parallel connections of PV modules.

Single module	Module voltage equal to load voltage
Several modules in series	Voltage of the array is higher
Several modules in parallel to form an array	Voltage is same as of one module. Higher current supplied to load.
Several arrays in parallel	- Voltage to load same as that of an array - Current of arrays are added.

Small Solar PV systems for residence:

Small solar PV systems are installed in residential buildings and provide electrical energy with following merits:

- Noiseless
- No fuel expenditure
- Modest maintenance
- Safe
- No pollution
- Long life

For lighting, heating and some low power applications, DC supply may be used. For other loads, AC supply is necessary. The solar collectors may be installed on slanting roof facing the south (For countries in northern hemisphere). The tilt angle and the orientation are decided before finalizing the plan of the house. Tilt angle should be approximately equal to the angle of latitude of the location.

Alternatively the PV panels may be installed on the roof or in open space on fabricated structure.

The solar PV system for homes may be one of the following:

- Stand-alone system if

- The house is away from distribution network. Such system needs storage batteries.

- System operating in parallel with AC Network. Such system need not have large storage capacity.

The No-return diode prevents return of current from the battery to the solar PV panel.

Voltage regulator and power conditioning unit regulates the output DC voltage and prevents overcharging of storage batteries. The functions of protection and control and conditioning of the output waveform are also performed.

Storage batteries store the electrical energy during bright sun light and low load hours.

Inverter converts DC to 50 Hz AC.

Large Solar PV Systems:

The ratings of medium Solar PV Diesel Generator Hybrid Systems are in the range of 5 kW to 350 kW.

Large central solar PV systems of MW range are not practically and economically feasible. A 100 MW Solar PV power station would require about 2.5 km^2 of PV cell surface area and total land area of about 5 km for PV collectors.

For Central Solar Power Plants of MW range solar Thermal Central Receiver Systems are preferred. Solar PV systems have been installed for ratings only up to 350 kW either with

Solar	- battery hybrid, or
Solar	- Battery, diesel generator hybrid.

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